AVIATION

ELECTRICIAN'S MATE 1 & C

BUREAU OF NAVAL PERSONNEL

RATE TRAINING MANUAL NAVPERS 10349-C

PREFACE

This Rate Training Manual is one of a series of Rate Training Manuals prepared especially for enlisted personnel of the Navy and Naval Reserve who are preparing for advancement to AE1 and AEC.

The Manual of Qualifications for Advancement, NavPers 18068 (Series), has been used as a guide in the selection of content for this training manual. Trainees should become familiar with the qualifications for advancement prior to starting work on this manual.

Of the 14 chapters in this training manual, 13 are concerned with the technical aspects of the AE rating. Chapter 1 contains introductory information with which the trainee should familiarize himself before studying the other chapters.

Basic Electricity, NavPers 10086 (current edition), and Basic Electronics, NavPers 10087 (current edition), contain essential background information for the AE rating. Some U.S. Armed Forces Institute courses, the content of which are closely related to the AE rating, are listed in the Reading List.

This Rate Training Manual has been prepared by the Navy Training Publications Center, NAS Memphis, Millington, Tennessee, for the Bureau of Naval Personnel. Credit is given to the Aviation Electrician's Mate School, Jacksonville, Florida, the Naval Examining Center, Great Lakes, Illinois, the Naval Aviation Logistic Support Center, Patuxent River, Maryland, and the Naval Air Systems Command for technical reviews.

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THE UNITED STATES NAVY

GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

CONTENTS

READING LIST

USAFI TEXTS

United States Armed Forces Institute (USAFI) courses for additional reading and study are available through your Educational Services Officer.* The following courses are recommended:

D-166 Advanced Algebra
D-177 Geometry II
D-188 Trigonometry
E-285 Chemistry I
E-286 Chemistry II
E-290 Physics I
E-291 Physica II
A-425 College Algebra
C-517 College Physics I
C-518 College Physics II
F-544 Personnel Management

*"Members of the United States Armed Forces Reserve components, when on active duty, are eligible to enroll for USAFI courses, services, and materials if the orders calling them to active duty specify a period of 120 days or more."

CREDITS

The Bureau of Naval Personnel is indebted to Litton Systems, Inc., for permission to use copyright passages and illustrations appearing in chapter 11. These materials were extracted from Fundamentals of Inertial Navigation.

CHAPTER 1

AVIATION ELECTRICIAN'S MATE RATING

This training manual is designed to aid the AE2 in preparing for advancement to AE1 and the AE1 in preparing for advancement to AEC. It is based primarily on the professional requirements or qualifications for AE1 and AEC, as specified in the Manual of Qualifications for Advancement, NavPers 18068 (Series). In preparing for advancement examinations, this manual should be studied in conjunction with Basic Electronics, NavPers 10087 (Series) and Military Requirements for Petty Officers 1 & C, NavPers 10057 (Series). The latter covers the military requirements for all senior petty officers.

It should be kept in mind that any changes in the professional qualifications occurring after the Change 5 revision of the "Quals" Manual may not be reflected in the information given in this manual.

In preparing this training manual, every effort has been made to cover professional matters adequately and yet within reasonable bounds. It has been designed to give the prospective AE1 or AEC a good working knowledge of all subjects covered by the professional qualifications for advancement. It includes new material required as a result of new equipment.

ENLISTED RATING STRUCTURE

The present enlisted rating structure includes two types of ratings: general ratings and service ratings.

GENERAL RATINGS are designed to provide paths of advancement and career development. A general rating identifies a broad occupational field of related duties and functions requiring similar aptitudes and qualifications. General ratings provide the primary means used to identify billet requirements and personnel qualifications. Some general ratings include service ratings; others do not. Both Regular Navy and Naval Reserve personnel may hold general ratings.

Subdivisions of certain general ratings are identified as SERVICE RATINGS. These service ratings identify areas of specialization within the scope of a general rating. Service ratings are established in those general ratings in which specialization is essential for efficient utilization of personnel. Although service ratings can exist at any petty officer level, they are most common at the PO3 and PO2 levels. Both Regular Navy and Naval Reserve personnel may hold service ratings.

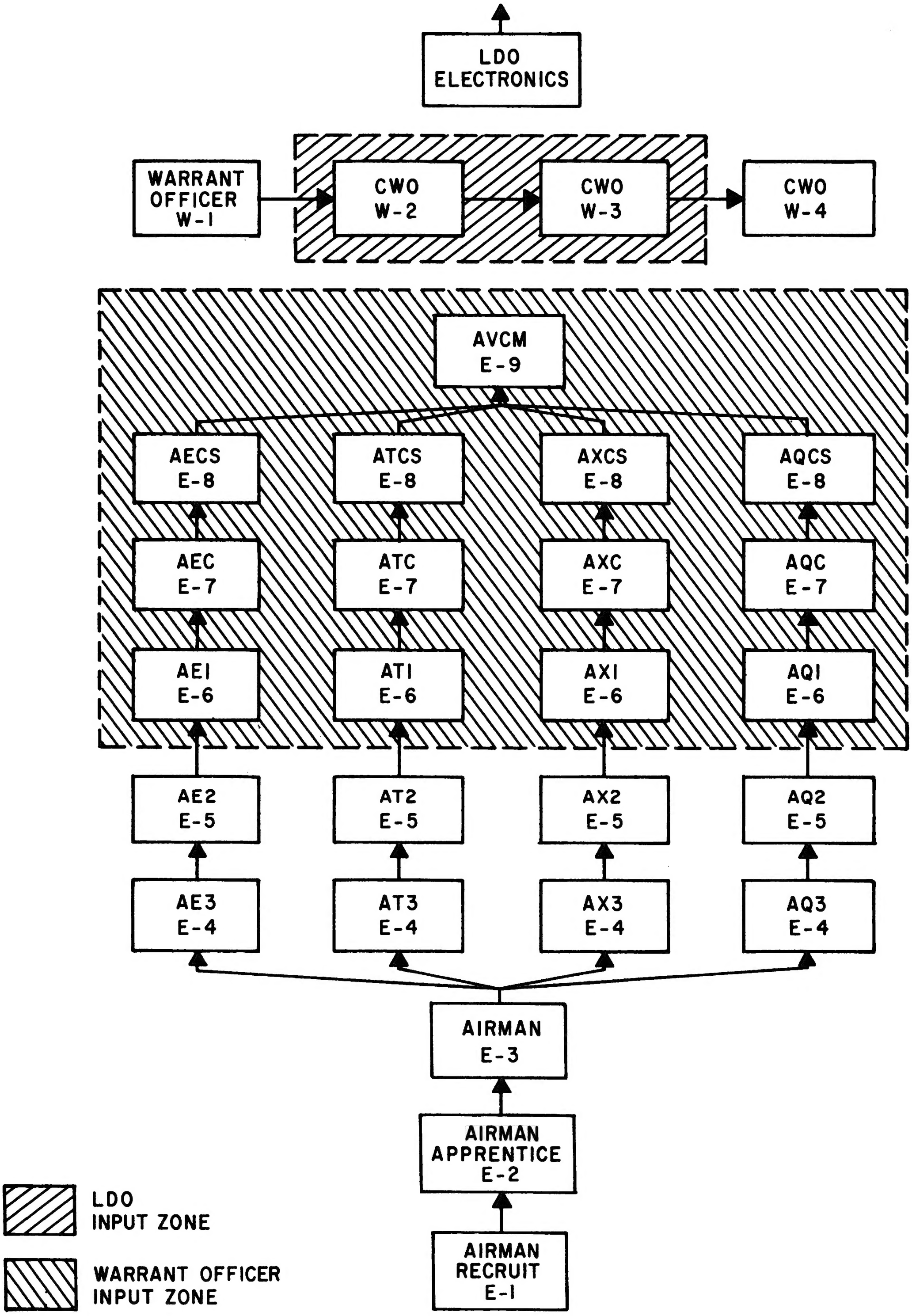
AE RATING

The Aviation Electrician's Mate rating is a general rating and is included in Navy Occupational Group IX (Aviation). There are no AE service ratings.

Where occupational content is related, general ratings have been combined at certain pay grades to form broader occupational fields. In the case of the AE rating, this takes place at the E-9 level. At this level the AE rating loses its identity and personnel in this rating advance, along with ATCS, AQCS, and AXCS to Master Chief Avionics Technician (AVCM). Figure 1-1 illustrates the paths of advancement from Airman Recruit to Master Chief Avionics Technician, Warrant Officer (W-4), or Limited Duty Officer. The advancement path through the AE rating is emphasized in the illustration.

Shaded areas in figure 1-1 indicate career status from which qualified enlisted personnel may advance to Warrant Officer (W-1), and selected Commissioned Warrant Officers (W-2 and W-3) may advance to Limited Duty Officer. Personnel in enlisted rates and Warrant ranks not in a shaded area (fig. 1-1) may advance only as indicated by the connecting arrows. Additional information concerning promotion to Warrant and Commissioned Officer is presented later in this chapter.

The Manual of Qualifications for Advancement, NavPers 18068 (Series), establishes the AE's technical responsibilities. The AE1 or AEC, working in a supervisory position, is required to review and evaluate completed inspection forms and reports; analyze reports of discrepancies and malfunctions and determine corrective action; schedule and assign



AE.1

Figure 1-1.—Paths of advancement.

workloads; determine repair procedures for aircraft electrical equipment; interpret directives from higher authorities; and maintain quality control of work performed.

When advanced to AE1 or AEC, even more responsibilities are to be yours. As a senior petty officer, you must possess more than technical knowledge. You must assume greater responsibility not only for your own work, but also for the work of others who serve under you. Briefly, the AE1 and AEC must be a supervisor, inspector, and instructor, as well as an accomplished military leader. Senior petty officers are therefore vitally concerned with the Naval Leadership Program.

As a result of the Naval Leadership Program, a considerable amount of material related to naval leadership for the senior petty officer is available. Studying this material will make you aware of your many leadership responsibilities as a senior petty officer and will also be of great help in developing leadership qualities. It will not in itself, however, make you a good leader. Leadership principles can be taught, but a good leader acquires that quality only through hard work and practice.

As you study this material containing leadership traits, keep in mind that probably none of our most successful leaders possessed all of these traits to a maximum degree, but a weakness in some traits was more than compensated for by strength in others. Critical self-evaluation will enable you to realize the traits in which you are strong, and to capitalize on them. At the same time you must strive to improve on the traits in which you are weak.

Your success as a leader will be decided, for the most part, by your achievements in inspiring others to learn and perform. This is best accomplished by personal example.

Assignments available to the AE's vary widely. In addition to the various types of maintenance activities to which lower rated personnel are assigned (discussed in AE 3 & 2, NavPers 10348), Second Class and above are eligible for assignment to instructor duty as well as a number of other desirable shore billets. Most of these billets are under the management control of BuPers and are directly associated with training. Others are associated with research, testing, or evaluation. Some of the more desirable billets to which the AE may be assigned are described in the following paragraphs.

Instructor duty is available at the Naval Air Technical Training Center, Jacksonville, Florida, in the following schools:

1. Aviation Electrician's Mate School (Class A).
2. Aviation Electrician's Mate Intermediate Course (Class B).
3. Aviation Electrician's Mate Advanced Course (Class B).

In addition to the above listed instructor billets, the AE may be assigned to instructor duty with a Naval Air Maintenance Training Detachment (NAMTD). NAMTD's are located at shore stations on both coasts. Personnel assigned to this duty are first sent to Naval Air Maintenance Training Group headquarters at Millington, Tennessee, for a period of indoctrination and instruction.

Instructor billets are normally filled on a voluntary basis. Detailed information concerning assignment to instructor duty is contained in the Enlisted Transfer Manual, NavPers 15909 (Series).

Chief Aviation Electrician's Mates are also eligible for assignment to duty with the Naval Examining Center, Great Lakes, Illinois, as Item Writers. CPO's assigned to the Examining Center assist in the preparation of Navy-wide advancement examinations for enlisted personnel.

Senior Chief Aviation Electrician's Mates are eligible for assignment to duty with the Navy Training Publications Center (NTPC) NAS, Millington, as Technical Writers. CPO's assigned to NTPC assist in the preparation and revision of Rate Training Manuals and/or Correspondence Courses for the avionics ratings.

There are a number of special programs and projects to which enlisted personnel may be assigned. Some of these involve research; others may involve testing or evaluation. An example of such an assignment is with the Naval Aviation Integrated Logistic Support Center (NAILSC), NATC, Patuxent River, Maryland. Their mission is to develop recommended personnel requirements for squadrons operating and maintaining the latest types of weapons systems.

For a listing of other special programs and projects, reference should be made to the Enlisted Transfer Manual. Others are also announced from time to time in BuPers Notices.

Personnel may indicate their desire for assignment to a specific program or project by indicating it in the "remarks" block of their Rotation Data Card.

ADVANCEMENT

By this time, you are probably well aware of the personal advantages of advancement—higher pay, greater prestige, more interesting and challenging work, and the satisfaction of getting ahead in your chosen career. By this time, also, you have probably discovered that one of the most enduring rewards of advancement is the training you acquire in the process of preparing for advancement.

The Navy also profits by your advancement. Highly trained personnel are essential to the functioning of the Navy. By advancement, you increase your value to the Navy in two ways: First, you become more valuable as a technical specialist, and thus make far-reaching contributions to the entire Navy; and second, you become more valuable as a person who can supervise, lead, and train others.

Since you are studying for advancement to PO1 or CPO, you are probably already familiar with the requirements and procedures for advancement. However, you may find it helpful to read the following sections. The Navy does not stand still. Things change all the time, and it is possible that some of the requirements have changed since the last time you went up for advancement. Furthermore, you will be responsible for training others for advancement; therefore, you will need to know the requirements in some detail.

HOW TO QUALIFY FOR ADVANCEMENT

To qualify for advancement, a person must:

1. Have a certain amount of time in grade.
2. Complete the required Rate Training Manuals either by demonstrating a knowledge of the material in the manual by passing a locally prepared and administered test or by passing the Enlisted Correspondence Course based on the Rate Training Manual.
3. Demonstrate the ability to perform all the PRACTICAL requirements for advancement by completing applicable portions of the Record of Practical Factors, NavPers 1414/1.
4. Be recommended by your commanding officer, after the petty officers and officers supervising your work have indicated that they consider you capable of performing the duties of the next higher rate.
5. Demonstrate KNOWLEDGE by passing a written examination on (a) military requirements, and (b) professional qualifications.

Some of these general requirements may be modified in certain ways. Figure 1-2 gives an overall view of the requirements for advancement of active duty personnel; figure 1-3 gives this information for inactive duty personnel.

Remember that the requirements for advancement can change. Check with your educational services office to be sure that you know the most recent requirements.

When you are training lower rated personnel, it is a good idea to point out that advancement is not automatic. Meeting all the requirements makes a person ELIGIBLE for advancement, but it does not guarantee his advancement. Such factors as the score made on the written examination, length of time in service, performance marks, and quotas for the rating enter into the final determination of who will actually be advanced.

HOW TO PREPARE FOR ADVANCEMENT

What must you do to prepare for advancement? You must study the qualifications for advancement, work on the practical factors, study the required Rate Training Manuals, and study other material that is required. You will need to be familiar with the following:

1. Manual of Qualifications for Advancement, NavPers 18068 (Series).
2. Record of Practical Factors, NavPers 1414/1.
3. Training Publications for Advancement, NavPers 10052 (Series).
4. Applicable Rate Training Manuals and their companion Enlisted Correspondence Courses.

Collectively, these documents make up an integrated training package tied together by the qualifications. The following paragraphs describe these materials and give some information on how each one is related to the others.

"Quals" Manual

The Manual of Qualifications for Advancement, NavPers 18068 (Series), gives the minimum requirements for advancement to each rate within each rating. This manual is usually called the "Quals" Manual, and the qualifications themselves are often called "quals." The qualifications are of two general types: (1) military requirements, and (2) professional or technical qualifications. Military requirements apply to

REQUIREMENTS*	E1 to E2	E2 to E3	#† E3 to E4	#E4 to E5	† E5 to E6	† E6 to E7	† E7 to E8	† E8 to E9
SERVICE	4 mos. service—or completion of	6 mos. as E-2.	6 mos. as E-3	12 mos. as E-4	24 mos. as E-5.	36 mos. as E-6. 8 years total enlisted service.	36 mos as E-7. 8 of 11 years total service must be enlisted.	24 mos. as E-8. 10 of 13 years total service must be enlisted.
SCHOOL	Recruit Training.		Class A for PR3, DT3,PT3, AME 3, HM 3, PN 3, FTB 3, MT 3.			Class B for AGC MUC, MNC.††		
PRACTICAL FACTORS	Locally prepared check-offs.	Record of Practical Factors, NavPers 1414/1, must be completed for E-3 and all PO advancements.						
PERFORMANCE TEST			Specified ratings must complete applicable performance tests before taking examinations.					
ENLISTED PERFORMANCE EVALUATION	As used hy CO when approving advancement.		Counts toward performance factor credit in advancement multiple.					
EXAMINATIONS**	Locally prepared tests.	See below.	Navy-wide examinations required for all PO advancements.				Navy-wide, selection board.	
RATE TRAINING MANUAL (INCLUDING MILITARY REQUIREMENTS)		Required for E-3 and all PO advancements unless waived because of school completion, but need not be repeated if identical course bas already been completed. See NavPers 10052 (current edition).					Correspondence courses and recommended reading. See NavPers 10052 (current edition).	
AUTHORIZATION	Commanding Officer		Naval Examining Center					

* All advancements require commanding officer's recommendation.
† 1 year obligated service required for E-5 and E-6; 2 years for E-7, E-8 and E-9.
Military leadership exam required for E-4 and E-5.
** For E-2 to E-3, NAVEXAMCEN exams or locally prepared tests may be used.
†† Waived for qualified EOD personnel.

Figure 1-2.—Active duty advancement requirements.

<table>
<tr><th>REQUIREMENTS *</th><th>E1 to E2</th><th>E2 to E3</th><th>E3 to E4</th><th>E4 to E5</th><th>E5 to E6</th><th>E6 to E7</th><th>E8</th><th>E9</th></tr>
<tr><td>TOTAL TIME IN GRADE</td><td>4 mos.</td><td>6 mos.</td><td>6 mos.</td><td>12 mos.</td><td>24 mos.</td><td>36 mos. with total 8 yrs service</td><td>36 mos. with total 11 yrs service</td><td>24 mos. with total 13 yrs service</td></tr>
<tr><td>TOTAL TRAINING DUTY IN GRADE †</td><td>14 days</td><td>14 days</td><td>14 days</td><td>14 days</td><td>28 days</td><td>42 days</td><td>42 days</td><td>28 days</td></tr>
<tr><td>PERFORMANCE TESTS</td><td colspan="2"></td><td colspan="6">Specified ratings must complete applicable performance tests before taking examination.</td></tr>
<tr><td>DRILL PARTICIPATION</td><td colspan="8">Satisfactory participation as a member of a drill unit in accordance with BUPERSINST 5400.42 series.</td></tr>
<tr><td>PRACTICAL FACTORS (INCLUDING MILITARY REQUIREMENTS)</td><td colspan="8">Record of Practical Factors, NavPers 1414/1, must be completed for all advancements.</td></tr>
<tr><td>RATE TRAINING MANUAL (INCLUDING MILITARY REQUIRE MENTS)</td><td colspan="8">Completion of applicable course or courses must be entered in service record.</td></tr>
<tr><td>EXAMINATION</td><td colspan="2">Standard Exam</td><td colspan="4">Standard Exam required for all PO Advancements. Also pass Military Leadership Exam for E-4 and E-5.</td><td colspan="2">Standard Exam, Selection Board.</td></tr>
<tr><td>AUTHORIZATION</td><td colspan="2">Commanding Officer</td><td colspan="6">Naval Examining Center</td></tr>
</table>

* Recommendation by commanding officer required for all advancements.

† Active duty periods may be substituted for training duty.

Figure 1-3.—Inactive duty advancement requirements.

all ratings rather than to any one rating alone. Professional qualifications are technical or professional requirements that are directly related to the work of each rating.

Both the military requirements and the professional qualifications are divided into subject matter groups. Then, within each subject matter group, they are divided into PRACTICAL FACTORS and KNOWLEDGE FACTORS.

The qualifications for advancement and a bibliography of study materials are available in your educational services office. The "Quals" Manual is changed more frequently than Rate Training Manuals are revised. By the time you are studying this training manual, the "quals" for your rating may have been changed. Never trust any set of "quals" until you have checked the change number against an UP-TO-DATE copy of the "Quals" Manual.

In training others for advancement, emphasize these three points about the "quals":

1. The "quals" are the MINIMUM requirements for advancement. Personnel who study MORE than the required minimum will have a great advantage when they take the written examinations for advancement.

2. Each "qual" has a designated rate level—chief, first class, second class, or third class. You are responsible for meeting all "quals" specified for the rate level to which you are seeking advancement AND all "quals" specified for lower rate levels.

3. The written examinations for advancement will contain questions relating to the practical factors AND to the knowledge factors of BOTH the military requirements and the professional qualifications.

Record of Practical Factors

Before you can take the Navy-wide examination for advancement, there must be an entry in your service record to show that you have qualified in the practical factors of both the military requirements and the professional qualifications. A special form known as the Record of Practical Factors, NavPers 1414/1 (plus the abbreviation of the appropriate rating), is used to keep a record of your practical factor qualifications. The form lists all practical factors, both military and professional. As you demonstrate your ability to perform each practical factor, appropriate entries are made in the DATE and INITIALS columns.

As a PO1 or CPO, you will often be required to check the practical factor performance of lower rated personnel and to report the results to your supervising officer.

As changes are made periodically to the "Quals" Manual, new forms of NavPers 1414/1 are provided when necessary. Extra space is allowed on the Record of Practical Factors for entering additional practical factors as they are published in changes to the "Quals" Manual. The Record of Practical Factors also provides space for recording demonstrated proficiency in skills which are within the general scope of the rating but which are not identified as minimum qualifications for advancement. Keep this in mind when you are training and supervising other personnel. If a person demonstrates proficiency in some skill which is not listed in the "quals" but which is within the general scope of the rating, report this fact to the supervising officer so that an appropriate entry can be made in the Record of Practical Factors.

When you are transferred, the Record of Practical Factors should be forwarded with your service record to your next duty station. It is a good idea to check and be sure that this form is actually inserted in your service record before you are transferred. If the form is not in your record, you may be required to start all over again and requalify in practical factors that have already been checked off. You should also take some responsibility for helping lower rated personnel keep track of their practical factor records when they are transferred.

A second copy of the Record of Practical Factors should be made available to each man in pay grades E-2 through E-8 for his personal record and guidance.

The importance of NavPers 1414/1 cannot be overemphasized. It serves as a record to indicate to the petty officers and officers supervising your work that you have demonstrated proficiency in the performance of the indicated practical factors and is part of the criteria utilized by your commanding officer when he considers recommending you for advancement. In addition, the proficient demonstration of the applicable practical factors listed on this form can aid you in preparing for the examination for advancement. Remember that the knowledge aspects of the practical factors are covered in the examination for advancement. Certain knowledge is required to demonstrate these practical factors and additional knowledge can be acquired during the demonstration. Knowledge factors

pertain to that knowledge which is required to perform a certain job. In other words, the knowledge factors required for a certain rating depend upon the jobs (practical factors) that must be performed by personnel of that rating. Therefore, the knowledge required to proficiently demonstrate these practical factors will definitely aid you in preparing for the examination for advancement.

NavPers 10052

Training Publications for Advancement, NavPers 10052 (Series) is a very important publication for anyone preparing for advancement. This publication/bibliography lists required and recommended Rate Training Manuals and other reference material to be used by personnel working for advancement. NavPers 10052 (Series) is revised and issued once each year by the Bureau of Naval Personnel. Each revised edition is identified by a letter following the NavPers number; be SURE you have the most recent edition.

The required and recommended references are listed by rate level in NavPers 10052 (Series). It is important to remember that you are responsible for all references at lower rate levels, as well as those listed for the rate to which you are seeking advancement.

Rate Training Manuals that are marked with an asterisk (*) in NavPers 10052 (Series) are MANDATORY at the indicated rate levels. A mandatory training manual may be completed by (1) passing the appropriate Enlisted Correspondence Course that is based on the mandatory training manual; (2) passing locally prepared tests based on the information given in the mandatory training manual; or (3) in some cases, successfully completing an appropriate Navy school.

When training personnel for advancement, do not overlook the section of NavPers 10052 (Series) which lists the required and recommended references relating to the military requirements for advancement. All personnel must complete the mandatory military requirements training manual for the appropriate rate level before they can be eligible to advance. Also, make sure that personnel working for advancement study the references listed as recommended but not mandatory in NavPers 10052 (Series). It is important to remember that ALL references listed in NavPers 10052 (Series) may be used as source material for the written examinations, at the appropriate levels.

Rate Training Manuals

There are two general types of Rate Training Manuals. Rate Training Manuals (such as this one) are prepared for most enlisted rates and ratings, giving information that is directly related to the professional qualifications for advancement. Subject matter manuals give information that applies to more than one rating.

Rate Training Manuals are revised from time to time to bring them up to date technically. The revision of a Rate Training Manual is identified by a letter following the NavPers number. You can tell whether a Rate Training Manual is the latest edition by checking the NavPers number (and the letter following the number) in the most recent edition of List of Training Manuals and Correspondence Courses, NavPers 10061 (Series). (NavPers 10061 is actually a catalog that lists current training manuals and correspondence courses; you will find this catalog useful in planning your study program.)

Rate Training Manuals are designed for the special purpose of helping naval personnel prepare for advancement. By this time, you have probably developed your own way of studying these manuals. Some of the personnel you train, however, may need guidance in the use of Rate Training Manuals. Although there is no single "best" way to study a training manual, the following suggestions have proved useful for many people:

1. Study the military requirements and the professional qualifications for your rate before you study the training manual, and refer to the "quals" frequently as you study. Remember, you are studying the training manual primarily to meet these "quals."

2. Set up a regular study plan. If possible, schedule your studying for a time of day when you will not have too many interruptions or distractions.

3. Before you begin to study any part of the training manual intensively, get acquainted with the entire manual. Read the preface and the table of contents. Check through the index. Thumb through the manual without any particular plan, looking at the illustrations and reading bits here and there as you see things that interest you.

4. Look at the training manual in more detail, to see how it is organized. Look at the

table of contents again. Then, chapter by chapter, read the introduction, the headings, and the subheadings. This will give you a clear picture of the scope and content of the manual.

5. When you have a general idea of what is in the training manual and how it is organized, fill in the details by intensive study. In each study period, try to cover a complete unit—it may be a chapter, a section of a chapter, or a subsection. The amount of material you can cover at one time will vary. If you know the subject well, or if the material is easy, you can cover quite a lot at one time. Difficult or unfamiliar material will require more study time.

6. In studying each unit, write down questions as they occur to you. Many people find it helpful to make a written outline of the unit as they study, or at least to write down the most important ideas.

7. As you study, relate the information in the training manual to the knowledge you already have. When you read about a process, a skill, or a situation, ask yourself some questions. Does this information tie in with past experience? Or is this something new and different? How does this information relate to the qualifications for advancement?

8. When you have finished studying a unit, take time out to see what you have learned. Look back over your notes and questions. Maybe some of your questions have been answered, but perhaps you still have some that are not answered. Without referring to the training manual, write down the main ideas you have learned from studying this unit. Do not just quote the manual. If you cannot give these ideas in your own words, the chances are that you have not really mastered the information.

9. Use Enlisted Correspondence Courses whenever you can. The correspondence courses are based on Rate Training Manuals or other appropriate texts. As mentioned before, completion of a mandatory Rate Training Manual can be accomplished by passing an Enlisted Correspondence Course based on the training manual. You will probably find it helpful to take other correspondence courses, as well as those based on mandatory training manuals. Taking a correspondence course helps you to master the information given in the training manual, and also gives you an idea of how much you have learned.

INCREASED RESPONSIBILITIES

When you assumed the duties of a PO3, you began to accept a certain amount of responsibility for the work of others. With each advancement, you accept an increasing responsibility in military matters and in matters relating to the professional work of your rate. When you advance to PO1 or CPO, you will find a noticeable increase in your responsibilities for leadership, supervision, training, working with others, and keeping up with new developments.

As your responsibilities increase, your ability to communicate clearly and effectively must also increase. The simplest and most direct means of communication is a common language. The basic requirement for effective communication is therefore a knowledge of your own language. Use correct language in speaking and in writing. Remember that the basic purpose of all communication is understanding. To lead, supervise, and train others, you must be able to speak and write in such a way that others can understand exactly what you mean.

Leadership and Supervision

As a PO1 or CPO, you will be regarded as a leader and supervisor. Both officers and enlisted personnel will expect you to translate the general orders given by officers into detailed, practical, on-the-job language that can be understood and followed by relatively inexperienced personnel. In dealing with your juniors, it is up to you to see that they perform their jobs correctly. At the same time, you must be able to explain to officers any important problems or needs of enlisted personnel. In all military and professional matters, your responsibilities will extend both upward and downward.

Along with your increased responsibilities, you will also have increased authority. Officers and petty officers have POSITIONAL authority—that is, their authority over others lies in their positions. If your CO is relieved, for example, he no longer has the degree of authority over you that he had while he was your CO, although he still retains the military authority that all seniors have over subordinates. As a PO1, you will have some degree of positional authority; as a CPO, you will have even more. When exercising your authority, remember that it is positional—it is the rate you have, rather than the person you are, that gives you this authority.

A Petty Officer conscientiously and proudly exercises his authority to carry out the responsibilities he is given. He takes a personal interest in the success of both sides of the chain of command . . . authority and responsibility. For it is true that the Petty Officer who does not seek out and accept responsibility, loses his authority and then the responsibility he thinks he deserves. He must be sure, by his example and by his instruction, that the Petty Officers under him also accept responsibility. In short, he must be the leader his title—Petty Officer—says he is.

Training

As a PO1 or CPO, you will have regular and continuing responsibilities for training others. Even if you are lucky enough to have a group of subordinates who are all highly skilled and well trained, you will still find that training is necessary. For example, you will always be responsible for training lower rated personnel for advancement. Also, some of your best workers may be transferred; and inexperienced or poorly trained personnel may be assigned to you. A particular job may call for skills that none of your personnel have. These and similar problems require that you be a training specialist—one who can conduct formal and informal training programs to qualify personnel for advancement, and one who can train individuals and groups in the effective execution of assigned tasks.

In using this training manual, study the information from two points of view. First, what do you yourself need to learn from it? And second, how would you go about teaching this information to others?

Training goes on all the time. Every time a person does a particular piece of work, some learning is taking place. As a supervisor and as a training expert, one of your biggest jobs is to see that your personnel learn the RIGHT things about each job so that they will not form bad work habits. An error that is repeated a few times is well on its way to becoming a bad habit. You will have to learn the difference between oversupervising and not supervising enough. No one can do his best work with a supervisor constantly supervising. On the other hand, you cannot turn an entire job over to an inexperienced person and expect him to do it correctly without any help or supervision.

In training lower rated personnel, emphasize the importance of learning and using correct terminology. A command of the technical languages of your occupational field (rating) enables you to receive and convey information accurately and to exchange ideas with others. A person who does not understand the precise meaning of terms used in connection with the work of his rating is definitely at a disadvantage when he tries to read official publications relating to his work. He is also at a great disadvantage when he takes the examinations for advancement. To train others in the correct use of technical terms, you will need to be very careful in your own use of words. Use correct terminology and insist that personnel you are supervising use it too.

You will find the Record of Practical Factors, NavPers 1414/1, a useful guide in planning and carrying out training programs. From this record, you can tell which practical factors have been checked off and which ones have not yet been done. Use this information to plan a training program that will fit the needs of the personnel you are training.

On-the-job training is usually controlled through daily and weekly work assignments. When you are working on a tight schedule, you will generally want to assign each person to the part of the job that you know he can do best. In the long run, however, you will gain more by assigning personnel to a variety of jobs so that each person can acquire broad experience. By giving people a chance to do carefully supervised work in areas in which they are relatively inexperienced, you will increase the range of skills of each person and thus improve the flexibility of your working group.

Working With Others

As you advance to PO1 or CPO, you will find that many of your plans and decisions affect a large number of people, some of whom are not even in your own occupational field (rating). It becomes increasingly important, therefore, for you to understand the duties and the responsibilities of personnel in other ratings. Every petty officer in the Navy is a technical specialist in his own field. Learn as much as you can about the work of others, and plan your own work so that it will fit into the overall mission of the organization.

Keeping Up With New Developments

Practically everything in the Navy—policies, procedures, publications, equipment, systems—is subject to change and development. As a PO1

or CPO, you must keep yourself informed about changes and new developments that affect you or your work in any way.

Some changes will be called directly to your attention, but others will be harder to find. Try to develop a special kind of alertness for new information. When you hear about anything new in the Navy, find out whether there is any way in which it might affect the work of your rating. If so, find out more about it.

SOURCES OF INFORMATION

As a PO1 or CPO, you must have an extensive knowledge of the references to consult for accurate, authoritative, up-to-date information on all subjects related to the military and professional requirements for advancement.

Publications mentioned in this chapter are subject to change or revision from time to time—some at regular intervals, others as the need arises. When using any publication that is subject to revision, make sure that you have the latest edition. When using any publication that is kept current by means of changes, be sure you have a copy in which all official changes have been made.

The reading list at the beginning of this manual consists of USAFI courses that offer additional background material. The educational services officer will always have the most up-to-date information and training manuals applicable to your rating.

In addition to training manuals and publications, training films furnish a valuable source of supplementary information. Films that may be helpful are listed in the U. S. Navy Film Catalog, NavAir 10-1-777.

ADVANCEMENT OPPORTUNITIES FOR PETTY OFFICERS

Making chief is not the end of the line as far as advancement is concerned. Proficiency pay, advancement to Senior (E-8) and Master (E-9) Chief, and advancement to Warrant Officer and Commissioned Officer are among the opportunities that are available to qualified petty officers. These special paths of advancement are open to personnel who have demonstrated outstanding professional ability, the highest order of leadership and military responsibility, and unquestionable moral integrity.

PROFICIENCY PAY

The Career Compensation Act of 1949, as amended, provides for the award of proficiency pay to designated military specialities. Proficiency pay is given in addition to regular pay and allowances and any special or incentive pay to which you are entitled. Certain enlisted personnel in pay grades E-4 through E-9 are eligible for proficiency pay. Proficiency pay is awarded in two categories: (1) Speciality pay—to designated ratings and NEC's, and (2) Superior performance pay—for superior performance of duty in certain specialities not covered by speciality pay. The eligibility requirements for proficiency pay are subject to change. In general, however, you must be recommended by your commanding officer, have a certain length of time on continuous active duty, and be career designated.

ADVANCEMENT TO SENIOR AND MASTER CHIEF

Chief petty officers may qualify for the advanced grades of Senior and Master Chief which are now provided in the enlisted pay structure. These advanced grades provide for substantial increases in pay, together with increased responsibilities and additional prestige. The requirements for advancement to Senior and Master Chief are subject to change but, in general, include a certain length of time in grade, a certain length of time in the naval service, a recommendation by the commanding officer, and a sufficiently high mark on the Navy-wide examination. The final selection for Senior and Master Chief is made by a regularly convened selection board.

Examination Subjects

Qualifications for advancement to Senior Chief Petty Officer and Master Chief Petty Officer have been developed and published in the Manual of Qualifications for Advancement, NavPers 18068 (Series). They officially establish minimum military and professional qualifications for Senior and Master Chief Petty Officers.

Training Publications for Advancement, NavPers 10052 (Series) contains a list of study references which may be used to study for both military and professional requirements.

The satisfactory completion of the correspondence course titled Navy Regulations, NavPers 10740-A4, is mandatory for advancement to E-8, and the course titled Military Justice in the Navy, NavPers 10993-A, is required of all personnel advancing to E-9.

ADVANCEMENT TO WARRANT AND COMMISSIONED OFFICER

The Warrant Officer program provides opportunity for advancement to warrant rank for E-6 and above enlisted personnel. E-6's, to be eligible, must have passed an E-7 rating exam prior to selection.

The LDO program provides a path of advancement from warrant officer to commissioned officer. LDO's are limited, as are warrants, in their duty, to the broad technical fields associated with their former rating.

If interested in becoming a warrant or commissioned officer, ask your educational services officer for the latest requirements that apply to your particular case.

CHAPTER 2
SUPPLY AND PUBLICATIONS

To have an effective aircraft maintenance program, the availability of spare parts and equipment is of prime importance. Without material the maintenance of an electrical system cannot be sustained. The roles of supply and maintenance and the responsibilities of each must be clearly understood by personnel at all levels.

In general, maintenance personnel have the responsibility to make known their requirements to supply. Supply personnel convert this demand to the proper format and obtain the required item. No attempt is made here to present a comprehensive study of the supply system. This chapter is to acquaint the AE with the aviation supply system to the extent that he should be able to understand what is required of him and the effects his actions have upon the supply support. Most emphasis is placed on local organization where the AE, as the ultimate consumer, is primarily involved. A brief discussion of the supply system is presented in an effort to familiarize the senior AE with basic supply principles used to provide his material requirements.

AVIATION SUPPLY

Aviation supply personnel are vital members of the aircraft maintenance team; and the AE, as well as other aviation maintenance ratings, must work in close harmony with them if successful teamwork is to be achieved. The team must work so that a flow of materials is maintained from the manufacturer to the man on the job. A correct concept of supply's relationship to the entire organization is essential in the supervision of aviation maintenance functions.

ORGANIZATION AND FUNCTION

The command exercising management control over the policies and procedures of the aviation supply organization is the Naval Supply Systems Command. The Commander of the Naval Supply Systems Command is usually a rear admiral who is appointed by the President for a term of 4 years with the advice and consent of the Senate. He works with the delegated authority of the Secretary of the Navy, and all orders emanating from him have the full force and effect of SecNav orders.

To better understand the relationship of the Naval Supply Systems Command to the Aviation Supply System, it might be well to quickly review the development of the Navy Supply System. Prior to 1842, the commanding officers of ships and stations were responsible for the procurement of their own supplies. They were furnished funds for this purpose by the Navy Department and were required to account for all expenditures. In addition to creating an intolerable burden of paperwork on the Navy Department, this procedure had the effect of forcing prices upward, especially when two commanding officers were bidding for some scarce commodity.

In 1842, Congress approved the establishment of a Bureau of the Navy to take cognizance over all matters of naval supply. The primary responsibilities of this infant supply bureau were the procurement, maintenance of custody, and issuance of naval material. They are the primary responsibilities of the Naval Supply Systems Command today. Every function of the Naval Supply Systems Command is directly related to one or more of these responsibility areas.

In the early years of naval aviation when the Navy had few aircraft, the procurement of spare parts was much like the old system whereby commanding officers dealt directly with the sellers to fill the needs of their command. The pioneer naval aviation project directors had to deal directly with the manufacturers as parts were required.

By 1917, the Naval Aircraft Factory (NAF) in Philadelphia had come into existence and was assigned responsibility for the procuring of aircraft and spare parts. Other responsibilities assumed by NAF include the repair of aircraft, the manufacture of some spare parts, and eventually the manufacture of complete aircraft. There are still many aviators around today

who earned their Navy wings in the old N3N, built by NAF.

In 1921, the Bureau of Aeronautics (BuAer) came into being and assumed the responsibility of procuring aircraft and aircraft engines. The responsibility for procuring spare parts and other aeronautical material remained with NAF, which until 1941 was the aviation supply center of the Navy.

The Aviation Supply Office (ASO) was established in 1941 under the technical control of BuAer and the management control of BuSandA. The function of ASO was the procurement, custody, and issuance of aeronautical spare parts and technical material. This is essentially the function of ASO today under the technical control of the Naval Air Systems Command. Management Control is vested in the Naval Supply Systems Command.

RESPONSIBILITIES OF THE NAVAL SUPPLY SYSTEMS COMMAND

The general functions of the Naval Supply Systems Command within its areas of responsibility include many that are not of primary interest to aviation maintenance personnel in that they are not related to aircraft maintenance. Some of the more important general functions of the Naval Supply Systems Command are as follows:

1. Supervises the procurement, receipt, custody, warehousing, and issuance of Navy supplies and materials, exclusive of ammunition and medical supplies.
2. Supervises and directs the operation of the supply phases of the Navy Supply System and administers the redistribution program of excess personal property within the Department of Defense and the sale of Navy surplus property.
3. Authorizes and supervises the transportation of Navy property.
4. Prepares budget estimates and administers funds for the supply distribution system.
5. Renders an annual report to the Congress of the money value of supplies on hand at the various stations at the beginning of each fiscal year and the disposition thereof, of the purchase and expenditure of supplies for the year, and of the balance on hand.
6. Coordinates the compilation of and arranges for the printing of the Catalog of Navy Material.

Some additional functions of the Naval Supply Systems Command that are of interest to naval aviation maintenance personnel are the general functions of ASO. These include the following:

1. Responsibility for overall determination of requirements, procurement, and distribution of standard aeronautical materials. (Certain materials excepted; e.g., complete aircraft and engines, complete electronic equipment, major photo equipment, nonstandard and experimental aerological equipment, and items of naval ordnance equipment.)
2. Maintenance of a complete file of ASO and Naval Air Systems Command contracts, letters of intent, amendments, extensions, and change orders, and distribution of copies of documents necessary to Navy field activities.
3. Stock control of aeronautical materials at all aviation supply facilities, including control of packing, preservation, and distribution of material under ASO cognizance to, from, and between aviation supply facilities and major supply points.
4. Maintenance of complete records of material on order and followup procedure necessary to effect timely deliveries for all material under ASO cognizance.
5. Maintenance of current records of existing storage facilities at depots, major supply points, and operation stations for aeronautical materials, and control of influx of materials in aviation supply channels so as not to exceed existing storage facilities.
6. Determination and disposition of obsolete and excess aeronautical material under Naval Air Systems Command cognizance.
7. Preparation and distribution of the Navy Stock List of the Aviation Supply Office, including interchangeability data.
8. Compilation and distribution of some allowance lists subject to approval by Naval Air Systems Command.
9. Compilation of lists of spare parts to be salvaged from surveyed aircraft.
10. Followup on delivery, stock recording, reallocating as necessary, and distributing change material promulgated by the Naval Air Systems Command.
11. Establishment and maintenance of a statistical unit which assembles, compiles, and analyzes usage data.
12. Maintenance of a representative at each aircraft manufacturer's plant who keeps ASO fully informed, as requested, as to all changes which affect spare parts under procurement.
13. Establishment of an inspection service which inspects aviation supply activities within established naval districts.

APPROPRIATIONS

At one time or another, almost everyone has had the frustrating experience of not being able to draw from supply some item that he thought necessary to have immediately; the usual reason given being, "We don't have any money left." It takes only a short time to realize that the Navy does not operate with unlimited funds. This section and the following section, titled "Allotments," are presented to further an understanding of the system whereby funds are made available at the user activity level for operating expenses.

The main money pool of the government is the General Fund of the Treasury. Funds come into the General Fund from such sources as income taxes, excise taxes, import-export taxes, etc. The only way for money to be expended from the General Fund is by congressional action, which has to be approved by the President. A bill passed by Congress which authorizes the expenditure of funds from the General Fund is called an appropriation.

An estimate of the amount of money required for the operation of the Defense Department during a given fiscal year is prepared by Department of Defense fiscal experts well in advance of the beginning of the fiscal year. The Congress studies the proposed budget in the light of world affairs, the current domestic economy, and such other considerations as they see fit, then acts upon it. They may increase the amount requested, decrease it, or pass it as submitted. After presidential action is completed, the money is made available to the Department of Defense to be spent during a specified year. This is known as an "annual" or "1-year" appropriation.

Congress and the President may also approve "no-year" appropriations for special projects such as large construction over an unspecified length of time. Another form of appropriation is the "multiple-year" appropriation for projects which will be completed in a predictable length of time. An example of this type of appropriation might be the money appropriated to cover the expenses of the NROTC college programs for the next 4 years.

The appropriation by which the AE is most affected is the current year appropriation. After the appropriation or expenditure authorization is received in the Department of Defense, it is prorated among the services as a percentage of their previously submitted budget estimates. The Navy's share is prorated among the various bureaus and commands in essentially the same manner; that is, as a percentage of their estimated requirements for the coming fiscal year. The money to be spent for naval aviation is made available to the Chief of Naval Operations. Here, part of the money is allocated to ASO for the purchase of aircraft spare parts in quantities which past usage data has indicated will probably be sufficient for the coming year. These spare parts are furnished to the operating activities at no cost, since their usage has been anticipated and the items paid for in advance. The account from which money was spent to buy these items is known as the Appropriation Purchase Account (APA). Material received in the user activities from this account is known as APA material.

Another part of the Chief of Naval Operations funds is made available to the operating activities in the form of operating budgets.

OPERATING BUDGETS

Budgets concerning naval aviation are authorizations by the Chief of Naval Operations to the user activities to spend a certain amount of money during a given length of time for specified purposes. User activities are shore commands which operate aircraft, and the major air type commanders. Major air type commanders are Commander, Naval Air Force, Atlantic (ComNavAirLant); Commander, Naval Air Force, Pacific (ComNavAirPac); Chief of Naval Air Training (CNATra); and Chief of Naval Air Reserve Training (CNAResTra). Operating funds for squadrons and units are apportioned to them by their type commander as an Operating Target (OPTAR). Routine nonaviation expenses for operating squadrons and units are absorbed by the ship or station to which assigned.

Flight Operations Budgets

Major air type commanders and shore commands which operate aircraft are furnished this budget by the Chief of Naval Operations. The OPTAR provided to fleet squadrons and units by their type commanders is a quarterly segment of these funds. Unused funds revert to the control of the type commander as each new OPTAR is authorized. Type commanders provide OPTAR's to all squadrons and units under their operational control, whether or not the user activity is based ashore. Shore station commanders have no responsibility for providing

money for the operation and line maintenance of aircraft of tenant fleet activities.

Funds allotted for the flight operation of aircraft are used only in direct support of the actual flight of the aircraft. By far the greatest expenditures against this budget are for fuel and oil. Other materials that may be purchased with this fund include crewman's flight clothing, liquid oxygen (LOX), and squadron administrative consumable office supplies.

Aviation Fleet Maintenance Budget

Air type commands are furnished this budget by the Chief of Naval Operations, then the air type command will furnish funds to ships by OPTAR. These funds are provided to finance the cost of intermediate and organizational levels of maintenance. These costs include the following:

1. Technical repair parts, common hardware, lubricants, cleaning agents, cutting compounds, metals, etc., incorporated into or expended in the performance of aviation maintenance of aircraft, aircraft engines, aeronautical components and subassemblies, and Navy maintenance of the Naval Air Systems Command authorized maintenance support equipment.
2. Fuels and lubricants consumed by aircraft engines in the performance of complete section repair.
3. Preexpended, consumable maintenance material.
4. Replacement of consumable/expendable allowance list items (Material Accountability and Recoverability Codes "B" and "C").

DISTRIBUTION SYSTEM

The aviation supply distribution system consists of reserve stock points, primary stock points, secondary stock points, and satellites. These are discussed briefly in the following paragraphs.

1. RESERVE STOCK POINTS carry reserve and backup stock for the aviation supply system. The range and quantity of stock are determined by the Aviation Supply Office. Reserve stock points provide stowage facilities for bulk material.
2. PRIMARY STOCK POINTS carry stock for their own consumption. They may be designated as support activities for secondary stock points, for fleet units, and/or yard and district craft in the area.
3. SECONDARY STOCK POINTS carry stock for their own consumption as well as stock for aircraft and assigned yard and district craft.
4. SATELLITES are aviation activities which are dependent for support on a primary or secondary stock point. Satellites are usually minor activities and normally receive their supply support on a retail issue outlet basis.

The consumer may be assigned to any of the primary, secondary, or satellite stock points for supply support. The same basic principles will affect your supply support. Hereafter in this training manual, they are referred to as field supply points.

MATERIAL IDENTIFICATION

As aviation maintenance personnel, we will be working closely with the aviation storekeepers in keeping aircraft in an "up" status. In order to obtain replacement parts as rapidly as possible, we must know how to determine the source of supply of different items. For example, we may waste many hours trying to find out that the item is to be manufactured within our own activity. Also, it is important to know the correct stock number and cognizance symbols used to requisition items from supply.

The cataloging system developed by the Department of Defense is such that it identifies with one name and stock number any item of supply that is carried in any or all government agencies. In the procurement of material it is normally necessary to identify your material requirement in the medium understandable to the supply system.

FEDERAL STOCK NUMBERS

Prior to 1952, each of the services had its own numbering system for identifying, cataloging, stocking, and issuing items of military supply. It was not unheard of that one service would be negotiating on the open market for an item that was held in surplus by another service under its own stock number. This confusion resulted in the passage in 1952 of the Defense Cataloging Standardization Act.

The implementation of the Defense Cataloging Standardization Act has resulted in a reduction of item duplication between the services by providing for one Federal Stock Number (FSN) for each item, regardless of the use of the item or the using activity.

The Federal Stock Numbering System was intended to create and improve standardization of items of military supply in servicewide use and reduce excess inventories which, for the most part, were caused by lack of standardization. Also, the reduction of excess inventories eliminates much financial loss due to material obsolescence.

NOTE: While reference in this chapter is made only to the military application, it should be noted that the Federal Stock Numbering System is the prime numbering system for all Federal agencies.

Types of Stock Numbers

In the Navy, ASO uses Federal Stock Numbers with prefixes composed of 1, 2, or 3 symbols, and suffixes composed of 2 characters which may be all letters or a combination of letters and numbers. When the prefixes and suffixes are used, the Federal Stock Number becomes a Coded Federal Stock Number. (See table 2-1.)

If a 1-symbol prefix is used, it designates the command or office having control or cognizance of a particular item. Some of the more common cognizance symbols, together with the type material controlled and the cognizant command or office, are listed in table 2-2.

Many variations of coded stock numbers will be encountered in field maintenance work. These variations indicate material management responsibilities for the item; flag certain items as recoverable, consumable, high value, etc.; and identify the condition of the material if it is not ready for issue. Some of the more common codes that an AE is likely to encounter include the following:

RH—a recoverable aeronautical component of high value.

2RHF—a recoverable aeronautical component of high value that is not ready for issue.

Because the variety of codes is so extensive and the trend to single service management of items has caused so many changes in recent years, a list of codes that might be prefixed or suffixed to a stock number would not be appropriate for this manual. The primary things to keep in mind are that the basic stock number, consisting of three groups of numerals, identifies the item from a technical point of view and that the other codes identify material management characteristics.

STANDARDIZATION OF ITEM NOMENCLATURE

The assignment of names of stock items is as important as the assignment of Federal Stock Numbers. When items are inducted into the supply system, official government nomenclature must be assigned. Often this item name plus additional descriptive data will differ from names of items previously used. If difficulty is experienced in locating a familiar item in the catalog, it is quite possible that the name has been changed to conform to a more general

Table 2-1.—Breakdown of a Coded Federal Stock Number.

2 RHF 1560-123-4567-BF

2R	Cognizance Symbol
H	Material Control Code
F	Material Condition Code*
1560 (first two digits)	Federal Group Code
1560	Federal Supply Classification Code (FSC)
123-4567	Federal Item Identification Number (FIN)
BF	Special Material Identification Code (SMIC)

*These codes will not appear in the Federal Stock Catalog; they are used only for material turn-in.

Table 2-2.—Cognizance symbols.

Symbol	Cognizant activity	Material controlled
0I	Naval Publications and Forms Center.	Publications.
1I	Naval Publications and Forms Center.	Forms.
1N	Electronics Supply Office.	Electronic assemblies and repair parts.
1R	Aviation Supply Office.	Consumable aeronautical material.
2G	Electronic Supply Office.	Electronic repair parts to support Naval Air System Command equipment.
2R	Aviation Supply Office.	Repairable aeronautical material.
2V	Naval Air Systems Command.	Aeronautical support equipment.
8R	Naval Air Systems Command.	Major aeronautical systems and equipment.
9G	Navy Fleet Material Support Office.	Navy-owned stocks of defense general material.
9N	Navy Fleet Material Support Office.	Navy-owned stocks of defense electronics material.

usage. For instance, it will be found that a "swab" is a small stick with a tiny wad of cotton on one end, and is used by the Medical Department. In order to clean the decks it will be necessary to think of another name for "swab." "Mops" will be found listed, together with the correct Federal Stock Number. Other examples are as follows: "Ceilometer" becomes "Projector, Cloud Height"; "Zipper" has become "Fastener, Slide Interlocking," etc.

MATERIAL IDENTIFICATION AIDS

There may be times when a part or some technical material is needed and the stock number is unknown. At other times some material may be on hand and its identity is not positively known. A knowledge of the several methods by which material may be identified is very helpful in speeding the completion of a maintenance task. There are many ways in which material may be identified. Certain data may be available which does not identify an item but may lead to positive identification. An aircraft part has a part number. The part number may be looked up in the IPB and identified by nomenclature and often by the stock number. If the stock number is not furnished in the IPB, it may be found by referring to the Cross-Reference Section C0006 of the Navy Stock List of ASO.

Some equipments have attached nameplates which provide such information as the manufacturer's name, make or model number, serial number, size, voltage, phase, etc. Identification data taken from the nameplate of the old part can be very helpful in procuring a replacement.

When only the description of the item is known, the best source for identification is the descriptive sections of the various Navy Stock Lists.

Various publications used in identifying material are described in the following paragraphs.

NavSup Publication 2002, Section VIII, Parts C and D

NavSup Publications 2002, Section VIII, Parts C and D contain a complete numerical listing of all available naval aeronautic publications distributed by the Naval Air Systems Command. This stock list is supplemented by and should be used in conjunction with NavAir 00-500A, Equipment Applicability List, NavAir 00-500B, Aircraft Application List and NavAir 00-500C,

Directives Application List. These lists are handy references to publications that should assist you in the identification of material.

Naval Material Catalogs

Naval Material Catalogs provide information necessary to procure items for operation and maintenance of activities afloat and ashore. The catalogs commonly used by aviation personnel are the Federal Supply Catalog for general stores and Navy Stock List of ASO for aeronautical material.

The Navy Stock List of the ASO contains catalogs or parts used in identifying aviation material. The parts of the Navy Stock List are as follows:

Part One—Cross-Reference Section. Section C0009 is used to cross-reference an FSN to manufacturer's part.

Part Two—Price and Management Data Section. This section contains a listing of FSN's whose items are under the inventory control of ASO. The Data Section is published according to the manufacturer of the part; for example, all Douglas airframe parts are listed in one book.

Part Three—Parts Listing Section. This section provides supply data to supplement information contained in the Illustrated Parts Breakdown. The following information is given for each item in this section:

1. Application checkoff list.
2. Repairable assemblies.
3. Supporting spare parts.

Part Four—Descriptive Section. The descriptive section is used when only the item nomenclature and physical characteristics are known. Illustrations are used when the item cannot be defined by words. The descriptive sections are published according to Federal Supply Classification.

Illustrated Parts Breakdown (IPB)

Illustrated Parts Breakdown lists are probably the most important tool for the identification of aeronautical material. As a senior Petty Officer, you are undoubtedly familiar with them. However, due to the importance attached to them as a material identification source, they are discussed briefly in the following paragraphs.

IPB's are compiled by the manufacturer for each aircraft model in naval use. IPB's, as discussed here, encompass IPB's for aircraft, IPB's for aircraft engines, and IPB's for individual accessories and equipments.

Although slight variations in format exist among the various IPB's each normally includes the following major sections.

1. TABLE OF CONTENTS. This section shows the breakdown of the catalog into sections and furnishes a cross-reference between the various assemblies and figures where they are illustrated. The section also cross-references assemblies and pages where they are broken down into subassemblies and parts.

II. INTRODUCTION. This section includes general information and instructions for using the publication. Because variations between IPB's do exist this section should be referred to prior to using an IPB with which you are not thoroughly familiar.

III. GROUP ASSEMBLY PARTS LIST. This section is the main text of the publications. It consists of a series of illustrations and parts lists in which all parts of the aircraft/engine/equipment are shown in assembly breakdown order. The illustrations and parts lists are keyed to each other by means of figure and index numbers. Each assembly included in the parts lists is followed immediately by its component parts properly indented to show their relationship to the assembly. The group assembly parts list is subdivided into groups such as wing group, tail group, and fuselage.

IV. NUMERICAL PARTS LIST. This section lists all parts in numerical order, and each part is cross-referenced to the figure and index number where it is illustrated. This list also shows the official source code of each part listed in the applicable IPB.

Source Codes

Item Source Codes are symbols which indicate to a consumer a source of supply for an item required to maintain or repair a component part of an aircraft. Specifically, these codes indicate whether the item is to be requisitioned from the supply system; to be manufactured; to be obtained from salvage; not to be replaced since the next higher assembly is to be installed; or, due to failure, is in need of complete overhaul or retirement of the assembly or equipment from service.

Source codes are assigned to material at the time of provisioning. Known or anticipated usage is the primary factor in the assignment of source codes. The ability to manufacture an

item within a naval activity is considered to be of secondary importance. In other words, items are normally source coded for purchase and stocking in the Navy supply system if usage is known or anticipated. Source codes for individual items may be revised as experience and usage develop.

The Naval Air Systems Command is responsible for the coordination and establishment of source coding policy. The responsibility for the source coding of aeronautical articles on formal provisioning is vested in the cognizant NavPlantRepO.

Source codes are published as a column of the numerical index of the Illustrated Parts Breakdown (IPB) and in other publications as directed by the Naval Air Systems Command. Figure 2-1 shows a portion of a page from the numerical index of the P-3A IPB.

NOTE: In some IPB's the numerical index is a separate volume, while in others it is a section of each volume.

The meaning of each source code is explained in the following paragraphs.

P Series—Purchased Items

SOURCE CODE P is applied to items which are purchased in view of known or anticipated usage and which are relatively simple to manufacture within the Navy if necessary.

SOURCE CODE P1 is applied to items which are purchased in view of known or anticipated usage and which are difficult, impractical, or uneconomical to manufacture within the Navy.

SOURCE CODE P2 is applied to items for which little usage is anticipated, but which are purchased in limited quantities for insurance purposes. Items coded P2 are difficult to manufacture, require special tooling or stock not normally available within the Department of the Navy, or require long production lead time.

SOURCE CODE P3 is applied to repair parts items which are purchased in limited quantity in accordance with life expectancy. Items coded P3 are normally deteriorative in nature and may require special storage conditions.

SOURCE CODE P4 is applied to items which are procured only for initial outfitting or for

Section II
Numerical Index

NAVWEPS 01-75PAA-4-14

PART NUMBER	FEDERAL STOCK NUMBER	VOL.. FIG. . INDEX	SOURCE CODE	ACCT/ REC. CODE	PART N
800053-101		1 - 26	U		800128-87
800053-103		1 - 26	P1	R	800128-89
		1 - 67			800128-9
800053-105		1 - 67	MF		800142-1
800053-11		1 - 26	U		800142-3
800053-13		1 - 26 - 19	P1	R	800142-5
		1 - 67 - 1			800144-29
800053-15		1 - 67	MF		800144-30
800053-17		1 - 67	MF		800144-31
800053-5		1 - 67 - 47	MF		800144-32
800053-9		1 - 67 - 48	MF		800172-11
800055		13 -240 - 3			800172-13
800056-15		1 - 81 - 43	P1	C	800172-17
800056-17		1 - 81 - 44	P1	C	800172-19
800056-19		1 - 81 - 45	P1	C	800172-23
800056-513		1 - 81	P1	R	800172-24
800056-515		1 - 81	X1		800172-7
800056-517		1 - 81	X1		800172-9
800056-519		1 - 81	P1	R	800173-10
800060-13			MO		800173-15
800060-14			MO		800173-19
800060-15			MO		800173-20
800060-16			MO		800173-21
800060-17			MO		800173-23
800061-10		1 - 3A	X1		800173-27
800061-11			MO		800173-29
800061-12			MO		800173-
800061-13					

AE.463

Figure 2-1.—Sample numerical index.

special control and not carried in system stock for replenishment purposes.

M Series—Manufactured Items

SOURCE CODE M is applied to manufactured items which are not purchased or stock numbered.

SOURCE CODE MO is applied to items which are capable of being manufactured within an organizational level maintenance activity.

SOURCE CODE MF is applied to items which are capable of being manufactured within fleet activities.

SOURCE CODE MH is applied to items which are capable of being manufactured within an intermediate maintenance activity (ashore).

SOURCE CODE MD is applied to items which are capable of being manufactured within a Naval Rework Facility.

A Series—Assemble—
Assembly Not Purchased

SOURCE CODE AO is applied to assemblies which are not purchased, but which are to be assembled within an overhaul/rework activity prior to installation. At least one of the items in the assembly must be coded in the P series which carries an individual part number and description.

SOURCE CODE AF is the same as code AO, but items are assembled in an intermediate maintenance activity (afloat).

SOURCE CODE AH is the same as code AF, but items are assembled in an intermediate maintenance activity (ashore).

SOURCE CODE AD is applied to items assembled within a Naval Rework Facility.

N Series—Purchased on
Demand—Not Stocked Normally

SOURCE CODE N is applied to items which do not meet established criteria for stocking and which are readily available from commercial sources; i.e., nuts, bolts, screws, washers, shims, rivets, knobs, cotter pins (not included in the Navy supply system), protective closures, bead chains, adhesives, and cabinet locks.

X Series—Normally Impractical
For Stocking—Not Procured

SOURCE CODE X is applied to items which, if damaged, would require uneconomical repair. The need for an item, or items, coded X will normally result in recommendation for retirement of equipment from service.

SOURCE CODE X1 is applied to items for which purchase of the next larger assembly source coded in the P series is justified.

SOURCE CODE X2 is applied to items which are not purchased for stock, but may be acquired for use through salvage or one time purchase. Activities requiring such items should attempt to obtain them from salvage; if not obtainable from salvage or readily manufactured, such items must be requisitioned through normal supply channels with supporting justification. Repeated requisitions may justify a change to the P series code.

U Series

SOURCE CODE U is applied when items are not of supply or maintenance stocking significance.

AERONAUTICAL ALLOWANCE LISTS

Aeronautical allowance lists are lists of equipment and material, known or estimated to be required, to place and maintain aeronautical activities in a material readiness condition. These lists contain substantially all items used with sufficient frequency to justify their issuance to all activities maintaining aircraft or equipment for which the lists are designed. They also contain information concerning stock number, nomenclature, interchangeability, and supersedures. These publications are further defined in subsequent paragraphs. Keep in mind that allowance lists normally contain support equipment allowed to maintenance personnel consistent with their assigned level of maintenance. Initial outfitting lists contain material of a spare parts nature required for maintenance of aircraft/equipments. Materials listed in the initial outfitting lists normally are held in supply stocks and under most conditions are not authorized shop spares.

Aeronautical Allowance Lists are reissued in accordance with reissue cycles established by the Naval Air Systems Command, or sooner, if required. Interim to reissues, the lists are maintained current by letters and by the issuance of Change Pages and Change Bulletins. Change Bulletins, which are official publications, are issued by ASO on a monthly basis, are numbered in consecutive numerical sequence within each calendar year, and are distributed to holders of allowance lists. For

checkoff purposes, a Change Bulletin Index is also published by ASO semiannually and distributed in the same manner as the Change Bulletins.

ALLOWANCE LISTS

Allowance lists indicate the range and quantities of support equipment considered necessary for maintenance support of assigned and/or supported aircraft. Generally, these items are in-use items required for daily or continual use, such as handtools and avionics test equipment.

Allowance lists are identified by the publication number NavAir 00-35Q, and those lists of primary importance are listed in the following paragraphs.

Section A, Standard Aeronautical Material and Naval Stock Account Material (NW 00-35QA-1)

Section A covers general material such as nuts, bolts, tubing, hose, paint, and other items common to the operation of all aircraft models. Both equipage and consumable supplies are shown. Quantities of consumable supplies appearing in section A are firm for initial outfitting and may be used as a guide for replenishment until sufficient usage data are available for determining requirements.

Section B, Aircraft Maintenance Parts

Section B contains airframe, engine, and accessories maintenance parts peculiar to each type of aircraft. A separate section B is issued for each model of aircraft. Quantities of items included in this section are based on the estimated number of flight hours to be flown for a given period of time (normally 90 days). Quantities of items appearing in the section B are firm allowances for outfitting only, and are used as a guide for replenishment until such time that sufficient usage data are available for determining requirements. Publication number example: NA-00-35QB-187, Initial Outfitting List for P-3A/B.

Section G, General Support Equipment For All Types, Classes, and Models of Aircraft (NA 00-35QG-016)

Section G (series) lists the quantities of handtools, handling and servicing equipment, and material which are made available for maintenance support of aircraft as may be assigned or supported.

Section K, Naval Aeronautical Publications and Forms (NA 00-35QK-1)

Section K outlines the general types and classes of aeronautical technical and training publications and forms which are provided as a commissioning allowance for various Navy and Marine Corps aviation activities. It lists those publications and forms which are issued by the Deputy Chief of Naval Operations (Air) and by the Naval Air Systems Command, but does not include publications provided to aviation activities by other Navy Department systems commands and bureaus, by fleet commands, or by non-Navy offices.

Section R, Aeronautical Electronic Material List (NA 00-35QR-Series)

This section comprises allowance lists of electronic equipment and material required for the test and maintenance of aeronautical electronic/armament equipments within the Naval Establishment.

Section T, Special Maintenance Support Equipment (NA 00-35QT-Series)

Section T lists the allowances of special support equipment for aircraft engines and accessories. The sections are divided into three parts—powerplants, accessories, and avionics.

INITIAL OUTFITTING LISTS

Initial outfitting lists (IOL's) are publications which indicate the range and quantities of maintenance spare parts considered necessary to support various aeronautical articles. This material is provided to vessels or activities and is firm only at the time of initial outfitting.

Increases and decreases in both range and/or quantities of material are based upon the experience (demand history) of each activity concerned. Each series list is designed to support an aircraft, electronic equipment, or some other aeronautical article. The allowances of material are established for various articles for a 90-day period. All items capable of replacement by a maintenance activity are not listed, but rather, only those that are expected to be used at least once in 9 months.

Initial Outfitting Lists are also identified by the publication number NavAir 00-35Q, and the pertinent lists are discussed in the following paragraphs.

Section X, Initial Outfitting List (NA 00-35QX-Series)

Section X lists spare parts, assemblies, and subassemblies required for the maintenance of armament, fire control, instruments, and electrical systems.

Section Z, Initial Outfitting List (NA 00-35QZ-Series)

Section Z lists special equipment and spare parts for aircraft, armament, and avionics support equipment.

TABLES OF BASIC ALLOWANCE

Publications listing equipment and material required for performance of specific functions are known as Tables of Basic Allowance. They contain both shop equipment and common supporting spare parts. They cover allowances of tools and equipment required for use by such activities as Fleet Marine Force squadrons and guided missile activities.

These publications are identified by the NavAir number 00-35T series.

MATERIAL REQUISITIONING

Maintenance personnel are apt to encounter a variety of local requisitioning channels, all designed to present a demand for an item to the supporting supply department. Assigned levels of maintenance, geographical location of shops relative to supply facilities, and mission of activities requiring support, all influence the local requisitioning channels. Local instructions normally promulgate detailed procedures for submitting your demand to the appropriate supply point.

SUPPLY FUNCTIONS

The mission of the supply activity is to support the operational and maintenance efforts of the activity/ship. Stocks of aviation oriented material carried are tailored and replenished to this end. Positioning replenishment, and control of stocks of material in maintenance areas are carried out as a result of joint decisions by the Supply and Maintenance Officers concerned. They determine the range, depth, and related procedures. The Navy Maintenance and Material Management System (Aviation) requires that the cost of material used in maintenance be determined and accumulated in such manner and detail that weapons system costing can be measured. Usage is finely defined as to stock number, within component, within system, within equipment/weapon/aircraft, in a particular squadron, located in a specific operational area, at a definite point in time. These data are used as an inventory management tool to determine geographic and strategic distribution of stocks of material. In addition, the data will be invaluable in establishing the material portions of work standards in maintenance.

Maintenance organizations have one point of contact with the supporting supply activity. This single supply contact point is the Supply Support Center (SSC) which responds to all material requirements of the maintenance organizations. The SSC is an internal organization, of the local supply activity. It is made up of three sections—the Supply Response Section, the Component Control Section, and the Supply Screening Section.

Supply support is available consistent with the operating hours of the maintenance activities supported. If maintenance is being performed 24 hours a day, then supply support is available 24 hours a day.

The Supply Support Center maintains rotatable pool material which consists of repairable ready-for-issue items reserved primarily to satisfy the requirements of organizational level maintenance. Items maintained in the pool are capable of being repaired by the local intermediate maintenance activity, have application relationship to weapon systems supported by local intermediate maintenance activities, and have an average organizational maintenance level removal rate of at least one per month.

Defective components are turned in to intermediate level maintenance for repair. The defective components repaired to an RFI condition are then returned to the rotatable pool to replace the components previously issued.

Low value, fast moving consumable items are preexpended from supply. Such materials are located in the maintenance area; and the establishment, maintenance, and replenishment of preexpended bins are the responsibility of the supply organization.

Supply Response Section

The Supply Response Section (SRS) is responsible for preparing all necessary requisitions (DD Form 1348) and related documents required to obtain material for local maintenance use in direct support of weapon system maintenance. The maintenance organization verbally notifies the supply organization of the need of such material. When material is available locally, the time frame for processing and delivery is as follows:

Priority	Process/delivery time
1-3	1 hour
4-8	2 hours
9-20	24 hours

Otherwise, the time frames as noted in table 2-3 will apply.

The SRS is responsible for receipt, storage, and issuance of all ready-for-issue pool components. It is responsible for physical delivery of RFI material to maintenance organizations, and the pickup of defective components from the organizational maintenance activity and subsequent delivery to the intermediate maintenance activity. Actual maintenance personnel are not involved in the physical movement of material between organizations.

This section also performs technical research in regard to completion of requisition documents as well as determining the status of outstanding requisitions and relaying this status to the customer upon request.

Component Control Section

The Component Control Section (CCS) accounts for all components being processed in the intermediate maintenance activities. This section also maintains records on the status of all rotatable pool components.

Supply Screening Section

The Supply Screening Section (SSS) is responsible for initiating disposition action on components that cannot be repaired by the local intermediate maintenance activity. Using listings and directives from inventory managers, screening personnel determine disposition of

Table 2-3.—Processing time frames.

Issue Group	Issue Priority Designator Range	Supply Source Processing	CONUS On Station Time	Overseas On Station Time
1	1-3	24-day workweek 24-hour day 7-day workweek	120 hours	168 hours
2	4-8	72 hours 24-hour day 7-day workweek	8 days	15 days
3	9-15	10 days 8-hour day 5-day workweek	20 days	45 days
4	16-20	12 days 8-hour day 5-day workweek	30 days	60 days

components in question, including prospective consignee and packaging and preservation requirements prior to movement of material.

MATERIAL CONTROL FUNCTIONS

The Maintenance/Material Control Officer in a maintenance activity is responsible for providing support and services to the production divisions. His primary purpose is to insure that maintenance requirements for parts and materials are made known to the supply organization in a timely manner in order to prevent work stoppages and grounding aircraft. Material control insures that parts and materials made available to maintenance are systematically utilized and not allowed to accumulate or to become depleted. It serves as the single point of contact within the maintenance organization for the conduct of business with the supply organization.

Material control provides material support to their cognizant organization by accomplishing the following general functions:

1. Pass all requirements for material required for direct support of weapon system maintenance to the SSC. A material control register is maintained for these items.
2. Prepare documents for materials required for indirect support of weapon system maintenance. Examples of materials for which documents are to be prepared are aviation fuels and lube oils, rags, and flight jackets. A separate requisition record log is maintained for these items.
3. Maintain liaison with the supporting SSC on maintenance material matters to insure that material needs of the organization are satisfied.
4. Establish delivery points for all material and insure that material received is expeditiously routed to the applicable work center.
5. Furnish technical advice and information to the supply activity on the identity and quantity of supplies, spare parts, and materials required for maintenance actions.
6. Establish procedures to insure the periodic inventory of tools and the adequate accountability of material and equipment on custody to the cognizant organization.
7. Initiate surveys in the event of loss, damage, or destruction of accountable material.
8. Keep maintenance control advised of the overall supply situation as it affects the activity.
9. Perform cost and allotment record accounting, charting, and budgeting of cost applicable to the cognizant organization.
10. Monitor the operation of toolrooms and maintain support equipment allowance lists.
11. Maintain inventory control of authorized allowances of material.

The Maintenance/Material Control Officer is responsible for the coordination of material ordering, receipt, and delivery. This is done in such a manner as to insure that the correct material is ordered and that it reaches the work center within the specified time frame.

The foregoing functions of the material control division apply to both organizational and intermediate level activities. Some of the functions which are applicable to one level only are listed in the following paragraphs.

Intermediate Level

An Administrative Screening Unit has been established in Material Control of intermediate maintenance activities. This screening unit does the following:

1. Positively identifies material and determines if it is within the repair capability of the Aircraft Intermediate Maintenance Department.
2. Insures that all required documentation is affixed to the component (i.e., logs, records, MAF, etc.).
3. Notifies maintenance control of the receipt of defective components for scheduling into the AIMD.
4. Transfers the defective components to the appropriate work center when directed by maintenance control.

All components received in the AIMD material control receive screening to determine if the item is within the check, test, or repair capability of the AIMD. As a result of this screening, components requiring maintenance within the AIMD capability are reported to maintenance control as ready for induction. Items beyond AIMD capabilities are returned to the Supply Support Center with appropriate recommendations for disposition. When work on components in the AIMD has been completed, the components, together with required records, are returned to Material Control for appropriate routing.

Organizational Level

In addition to the general functions, Material Control in organizational level activities is responsible for the following:

1. Verification of NORS (Not Operationally Ready Supply) requisitions and maintain current NORS status records.
2. Inventory of aircraft upon receipt and transfer and maintenance of inventory records.

When removed components are generated as a result of the maintenance effort, Material Control insures that the SSC is notified to make a pickup. These components must be accompanied by record cards and logs, when applicable, plus the number two, three, and four copy of the MAF.

Material Control Register

The Material Control Register is used by intermediate and organizational level activities to record all materials requested from the supply support center in direct support of weapon system maintenance. Space is provided to record essential information considered necessary to monitor OPTAR funds. This information includes part number, priority, quantity, price, date, and time ordered, and date and time received. Maintenance control uses the time ordered and time received to help determine NORS time used in fulfilling readiness reporting requirements.

When a defective repairable item is turned in, the following forms are required: copies two, three, and four of the multicopy MAF and the Schedule Removal Component Form, OpNav 4790/27A, when applicable. The supply department will detach copy two of the MAF for bookkeeping purposes. Copies three and four of the MAF accompany the item to the AIMD. When repair is completed by the AIMD, copy four of the MAF is attached to the RFI item and the item is returned to the supply system.

If material being turned in is no longer required and is RFI, a Single Line Item Release/Receipt Document (DD 1348-1) is submitted with the item. RFI means ready for issue in all respects—preservation still intact and item in original or reusable container with seals unbroken.

MILSTRIP

The Military Standard Requisitioning and Issue Procedure (MILSTRIP) and Uniform Material Issue Priority System were developed by the Department of Defense to provide a common supply language and more effective supply system operations within the military establishment. This system standardizes forms, formats, codes, procedures, and the priority system.

MILSTRIP employs two forms for the requisitioning and issuing of material. The Single Line Item Requisition Document (Form DD 1348) is the basic request document submitted to the applicable supply echelon for material requirements. The issue document is the Single Line Item Release/Receipt Document (Form DD 1348-1). Form DD 1348-1 is also used to return RFI material to the supply system. These forms will be prepared by the Supply Response Section of supply for all material requested in direct support of weapon system maintenance and by the Material Control for material requested in indirect support of weapon system maintenance.

Uniform Material Movement and Issue Priority System (UMMIPS)

In this system, the priority designator is determined by a combination of factors which relate the military importance of the requisitioner (force/activity designator) and the urgency of need or end use (indicated by an urgency-of-need designator). The force/activity designator (a roman numeral I-V) is assigned by the Joint Chiefs of Staff (JCS), Chief of Naval Operations (CNO), and Navy commanders. The urgency-of-need designator (an alphabetical letter) is determined by the requisitioning activity, with certain exceptions. These two factors will enable the requisitioning activity to determine the UMMIPS priority designator (arabic numeral).

The twenty priority designators provided in UMMIPS have been placed into four priority groups. Each priority group qualifies for different processing time standards as prescribed in table 2-4. These priority groups are compatible with the transportation priorities prescribed in the Military Standard Transportation and Movement Procedures (MILSTAMP).

1. Force/activity designators.
   a. A force/activity is:
      (1) A unit, organization, or installation performing a function or mission.
      (2) A body of troops, ships, or aircraft, or a combination thereof.

(3) A function, mission, project, or program, including those under military assistance (grant aid and/or sales).

2. Selection and assignment of issue priority designators for requisition and issue transactions.

a. All requests for material normally stocked in a supply system will be assigned an issue priority designator. The issue priority designator normally expresses the relationship between the force/activity designator and the urgency-of-need designator. However, there are certain exceptions and unusual circumstances under which a requisitioning activity is authorized to assign a specific numerical priority designator that represents a uniform need for an item regardless of the force/activity designator assigned. These exceptions are as follows:

(1) A priority designator of 03 will be used by all activities regardless of force/activity designator in requisitioning high value items required for immediate use; i.e., where urgency-of-need designators A or B are indicated.

(2) A priority designator of 03 will be used by all activities, regardless of force/activity designator, for medical or disaster supplies or equipment required immediately for prolonging life in case of critical injury, fatal disease, or natural emergency.

(3) A priority designator of 06 will be used by all activities, regardless of force/activity designator for the replenishment of high value items.

(4) A priority designator of 06 will be used by all activities regardless of force/activity designator, for individual and organizational clothing required to provide a minimum of essential clothing in the event active duty military personnel are without the clothing required.

b. Except for conditions referenced above, the requisitioner will:

(1) Select the applicable urgency-of-need designator for each requisition or order.

(2) Ascertain the appropriate issue priority designator for the force/activity designator assigned the requisitioning activity and the applicable urgency-of-need code, and enter this number on the material requirement document (NAVSTRIP requisition).

c. Supply activities, when requisitioning a specific requirement for a supported unit with a different force/activity designator than the supplying activity, will use the priority designator appropriate to the requiring activity.

3. Every activity is assigned 1 of 5 force/activity designations according to their military importance. (See table 2-4.) These designators are as follows:

I - COMBAT—The highest order of military importance. This designator is not normally used in peacetime unless approved by the President or the Joint Chiefs of Staff.

II - POSITIONED—United States combat, combat ready, and direct combat support forces deployed outside CONUS in specific theaters or areas designated by the Joint Chiefs of Staff and those CONUS forces being maintained in a state of combat readiness for immediate (within 24 hours) deployment or employment.

III - READY—All other United States combat ready and direct combat support forces outside CONUS not included under designator II.

IV - RESERVE AND SUPPORT—U.S. active and selected reserve forces planned for employment in support of approved joint war plans. This category includes training units and units in training for scheduled deployment.

V - OTHERS—All units not otherwise assigned, including administrative/staff type units.

4. The urgency of need for an aircraft spare part or aeronautical material may be determined

Table 2-4.—Priority number chart.

Designator	A Unable to perform	B Impairs capability	C Other than routine	D Routine
I Combat	1	4	11	16
II Positioned	2	5	12	17
III Ready	3	6	13	18
IV Reserve and support	7	9	14	19
V Others	8	10	15	20

in accordance with the following designators (A, B, C, and D):

A – Emergency requirements for primary weapons, equipment, and material for immediate use without which the unit concerned is unable to perform assigned operational missions (NORS), or such condition of readiness is imminent. (See notes 1 and 2.)
 Material required for immediate installation on or repair of primary weapons and equipment, without which the unit concerned is unable to perform assigned operational missions (NORS), or such condition of readiness is imminent. (See notes 1 and 2.)
 Items required for immediate end use in direct support of equipment essential to the operation of aircraft and equipment (e.g., ground support, firefighting, etc.), or such condition of readiness is imminent. (See notes 1 and 2.)

B – Item(s) required for immediate end use, the lack of which is impairing the operational capability of the aircraft or organizational unit concerned. The aircraft or organizational unit concerned can operate only temporarily as an effective unit; assigned operational missions can be accomplished, but with decreased effectiveness and efficiency.
 Item(s) required for immediate end use to effect repairs to aircraft and aircraft support equipment, without which the operational capability of the aircraft is impaired or effectiveness in accomplishing assigned missions is reduced.
 Item(s) required to effect emergency repair or replacement of intermediate maintenance activity equipment essential to providing services for aircraft and aircraft equipment.

C – Items required for immediate end use to repair or replace administrative support equipment and equipment or systems not essential to operational missions of aircraft or organizational units.

 Items essential to initial outfitting or to completion of allowance/load lists on a more urgent basis than routine stock replenishment.
 Material required to preclude a work stoppage or prevent delay in scheduled maintenance of weapons systems or major equipment.

D – Items required for routine stock replenishment.
 Items required for initial outfitting and filling of allowances.
 Items required for scheduling maintenance, repair, or manufacture of supply system stocks.

NOTE 1: Requirements of this nature are of such a consequence as to require a report to higher authority of a degradation of the requisitioning units capability.

NOTE 2: An imminent condition of degraded readiness exists when material is required to prevent an Anticipated Not Operationally Ready Supply (ANORS) condition. An ANORS condition will exist when it is known that items of material or equipment, not available in the unit, are required within the following time frames:

a. Five (5) days for nondeployed units.
b. Seven (7) days for deployment units.
c. Fifteen (15) days for Vietnam requirements.

PARTS KITS

Parts kits contain supporting items and material for the maintenance, repair, and rework of selected aeronautical repairable type items and will be procured, stocked, requisitioned, accounted for, and used on a kit basis as one line item.

A parts kit consists of a group of maintenance or overhaul parts that are bought, packaged, and stocklisted as a single item regardless of classification that may be included therein. Normally, these parts have either a very low unit cost or have a high replacement rate in overhaul or repair of the next higher assembly. Depending on the complexity of the end item, there can be one or more kits needed for its repair. Parts kits are designed to serve three separate requirements as described in the following paragraphs.

C KIT (CURE-DATED OR SOFT GOODS). This kit provides cure-dated items such as diaphragms, packing, and O-rings. The C kit may also contain soft goods not subjected to age control such as gaskets and seals, plus metallic items such as screws, nuts, and washers required to be removed when cure-dated or soft goods type materials are replaced. Any metallic

item placed in the C kit is not duplicated in the D kit. When mixed categories or cure-dated parts are packaged in a single container, the control or cure-date of the package must be that of the oldest cure-dated part contained therein. If cure-dated kits become overaged due to the expiration of the storage limitations, the kit must be administratively disposed of as excess material.

D KIT (OVERHAUL). This kit provides hard good spare parts required for overhaul of equipment by depot level maintenance. This kit does not contain cure-dated parts.

F KIT (FIELD). This kit provides those items that are required to be replaced at intermediate and organizational maintenance levels. These parts are normally items not requiring special tools or equipment. This kit does not contain cure-dated parts.

Part numbers for applicable parts kits for intermediate and organizational levels of maintenance are listed in the Illustrated Parts Breakdown and the Maintenance Instructions Manual. Components of kits are additionally identified in the Illustrated Parts Breakdown by a footnote and a symbol appearing to the right in the part number column and indicating which items are furnished in the kit. The Maintenance Instructions Manual utilizes a symbol keyed to the illustration to indicate parts furnished in the kit.

Presence of a new part in an applicable parts kit eliminates the necessity of cleaning, inspection, or rework of the equivalent part removed from the assembly being repaired. Removed parts in this category must be administratively condemned. Removed parts not supplied in applicable kits must be handled in accordance with instructions contained in the Maintenance Instructions Manuals.

Detailed instructions on parts kits are contained in BuWeps Instruction 4423.8.

PREEXPENDED BINS

A preexpended bin is one which contains low cost, high usage items which have already been charged to final expenditure. Many items of small dollar value are used repetitively in the aircraft maintenance program. The accepted practice is to stock these repetitively used items in the immediate maintenance area in a semicontrolled preexpended bin. Preexpended bins are normally established by the supply department in consort with the maintenance activity and are labeled, stocked, and replenished by the supply department. The normal responsibilities of maintenance personnel in this are:

1. Recommending items to be stocked.
2. Supervising the use of the bins to prevent waste, pilferage, and deterioration of the contents to a scrap heap.
3. Insuring that preexpended bins are separate and distinct from the normal "salvage" boxes located in most shops.

Preexpended bins provide repetitively used items to maintenance personnel with the minimum of effort. The material is immediately available to all shop personnel. The bins also provide the supply department with a constant and realistic demand history.

Nonstandard and/or Navy manufactured items may at times be required. These are normally obtained through the normal supply channels as outlined in local directives.

Manufactured items are those items which are source coded in the M series in applicable illustrated parts breakdown lists. Request documents submitted for manufactured items should contain additional reference data such as, part number, drawing number, and publication reference, or any other information which would be advantageous in the acquisition of the material.

Nonstandard material (material requiring open purchase) may not be procured when standard stock items are available except when the nonstandard material is considered to be indispensable. When the procurement of nonstandard material is considered essential, the originating request document must contain the following information:

1. A certification that no standard stock material is suitable.
2. A justification for the procurement of the nonstandard material.

ROTATABLE POOLS

Rotatable pools consist of a range of selected components maintained by a specific maintenance activity, on custody from the supporting supply department. The items generally carried in the pool are those required to sustain operations where immediate availability is essential. Aircraft wheels, tires, avionics assemblies, propellers, and carburetors are examples of items that might be included in the pools. The range and quantity of items to be carried in the pool are subject to the recommendations of the maintenance activities. The supply

department establishes the rotatable pool stock and prescribes detailed procedures for operation and control of the pool

ACCOUNTING FOR MATERIAL IN USE

Accounting for material does not cease when it is withdrawn from the supply department. It is at this point that the accounting responsibility passes to the applicable maintenance personnel.

AIRCRAFT PARTS

Normally, the accounting for aircraft parts drawn to replace similar defective parts is satisfied when the part is installed on the aircraft. No further custodial records are required. The accounting for materials drawn for general maintenance is satisfied when the material is consumed in the authorized maintenance work. In these cases it is actually the removed defective material that required additional action to insure its accountability from the time it is removed until it is returned to the supply department.

Accountability Codes

The degree of accountability required for aeronautical material may be ascertained by the material accountability recoverability codes (MARC). Material accountability recoverability codes are a part of the source, maintenance, and recoverability codes which are assigned provisioned items as required by current ASO and BuWeps/NavAir directives. The MARC's appear in the descriptive sections and parts lists sections of the ASO Navy Stock List, NavAir Allowance Lists, and may appear in such other publications as directed by NavAirSysCom. These codes aid personnel to determine the proper method of:

1. Requisitioning material.
2. Accounting for material while in use.
3. Turn-in or disposition of material.
4. Repair or overhaul of material.

The following list defines the various material accountability codes.

B – Exchange Consumables. Code B is applied to items which are consumable or expendable but normally require item-for-item exchange for replacement. Such items may contain precious metals, may be highly pilferable, or may be high cost items.

C – Consumables. Code C is applied to all other consumable or expendable items which do not require item-for-item exchange for replacement.

D – Equipage, Support Type. Code D is applied to end items of support equipment which are economical and practical to repair on a scheduled basis through a major rework activity. Code D items are maintained on a custodial basis and normally require item-for-item exchange for replacement.

E – Equipage, Locally Repairable, Support Type. Code E is applied to end items of support equipment which are to be repaired locally by the using or fleet support activity within their assigned maintenance responsibility. Code E items are maintained on a custody basis and normally require item-for-item exchange for replacement.

R – Equipage. Code R is applied to repairable (except end items of support equipment) items which are economical and practical to repair on a programed basis through a major rework activity. Code R items are maintained on a custody basis in some cases, depending upon the use of the item. These items normally require item-for-item exchange for replacement.

L – Equipage, Locally Repairable. Code L is applied to repairable (except end items of support equipment) items which are to be repaired locally by the using or fleet support activity within their assigned maintenance responsibility. Code L items are maintained on a custody basis in some cases, depending on the use of the item. They will normally require item-for-item exchange for replacement.

Some allowance lists may still be in use which utilize a different accountability code system than MARC. The following equivalents may apply, pending issuance of new publications using the latest material accountability recoverability codes:

MARC	INTERIM	OLD
D	A	A
D	O	A
D	E	AX

MARC	INTERIM	OLD
R	R	X
B	D	NONE
C	C	C
E	NONE	NONE
L	NONE	NONE

As is apparent upon reviewing the material accountability recoverability codes, the disposition of defective material is largely dependent upon its potential repairability. Codes D, E, R, and L signify that the item is repairable and is required to be returned to the supply system even though it is not RFI. The need for the expeditious handling of prospective repairable material cannot be overemphasized. The repair program is the prime source of supply for many critical high value items. Code C items are normally consumed or are not of a repairable nature and do not require turn-in if non-RFI.

An aeronautical material screening unit is established by all activities assigned the responsibility to perform intermediate level maintenance. The basic responsibility of the screening unit is to screen all defective aeronautical material generated on the station by tenant squadrons and station operating units prior to further processing of the material by the supply system or higher echelons of maintenance. The screening unit determines if such material is within the repair responsibility of local intermediate maintenance activities and, if so, initiates action to effect its local repair.

Normally, the following sequence of events should be followed in the repair of aeronautical material:

1. The using activity should repair the defective item without removal from the aircraft.
2. The using activity should remove the defective item from the aircraft, check, test, and repair it within their assigned responsibilities and replace it on the aircraft.
3. In the event the item requires repair and the time involved is excessive from the operational or readiness point of view, the using activity may draw a replacement item from supply. The defective item should be forwarded to the supporting intermediate maintenance activity's screening unit.
4. This screening unit determines if the item is within the repair responsibility of the intermediate maintenance activity, and, if so, the item is repaired and forwarded to supply as RFI. If not, the item is forwarded to supply as prospective repairable material.

AIRCRAFT MAINTENANCE SUPPORT EQUIPMENT

Developing and supervising proper procedures to insure the maintenance and accountability of aircraft maintenance support equipment (AMSE) is normally a prime administrative function of the electrician. Unlike most aircraft parts, AMSE requires the maintenance of custodial records and periodic physical inventories throughout its in-use life.

Aircraft maintenance support equipment is discussed in this chapter applies to all accountable type support equipment listed in NavAir Allowance Lists. Accountable AMSE items are those assigned material accountability recoverability codes "D" and "E". These items are assigned material control code X which appears as part of the federal stock number identification.

Because stocks of AMSE are so limited, issues are strictly controlled to insure proper program support. After initial outfitting, AMSE items are issued on an item-for-item exchange basis. When an AMSE item is lost, missing, or beyond economical repair, and replacement is required, approval of the replacement item is granted only when accompanied by a copy of the survey document. Aircraft maintenance support equipment is issued by the supply activity to the end user only upon approval by the following:

1. The cognizant type commander or his designated representative for fleet and training command activities.
2. The cognizant NavAirSysComRep for Naval Air Rework Facilities and shore activities.
3. ASO for special programs, bailment programs, military aid programs (MAP), etc.

Aircraft maintenance support equipment includes such items as test stands, lubricating guns, special wrenches, drills, compass testers, and voltmeters as listed in the Allowance Lists mentioned above. These equipments are made available as organizational property or custody/subcustody from supporting station/squadron/vessel dependent upon the characteristics of the equipment and the assigned maintenance, operational, and/or logistics responsibilities.

Under the aircraft maintenance material readiness list (AMMRL) program all applicable intermediate and/or organizational maintenance support equipment listed in the various allowance lists are consolidated into one individual

material readiness list (IMRL) for each aircraft maintenance activity. Each IMRL is approved by the cognizant fleet or training command and is used as the firm mandatory material readiness list of the activity to which the list applies.

All aircraft maintenance support equipment must receive continued accountability while in use. The activity having prime custody of the support equipment is considered to be the accountable activity. Equipment furnished as organizational property is accountable activity. Equipment furnished as organizational property is accounted for by the holder of such equipment. Equipment furnished or received on subcustody is accounted for by the supporting activity.

The department head is held responsible for the maintenance support equipment in his department. Senior Petty Officers normally are required to receipt on subcustody for all the AMSE in their shops. Periodic inventories are required to ascertain if material for which you are responsible is actually on hand. Material which cannot be accounted for must be surveyed.

An annual inventory of in-use aircraft maintenance support equipment is required to provide ASO and Naval Air Systems Command with an accurate assessment of the quantity and condition of this support equipment in the possession of custodians in order that sound decisions can be made concerning the procurement of new and replacement equipment. Type commanders or the NavAirSysComRep forwards to all activities having reportable items of support equipment a deck of EAM cards and/or an EAM listing indicating those items of support equipment requiring inventory. Care should be taken to insure that items held or issued on a custody basis are reported only by the controlling custodian.

Transaction reporting of selected AMSE items is sometimes required. Type commanders or the NavAirSysComRep selects the items of AMSE desired to be reported on a transaction basis and publish appropriate instructions for reporting. Upon receipt or transfer of an item of AMSE (subject to transaction reporting) on a permanent basis, or when the condition or status of equipment changes, activities are required to submit a transaction report.

HIGH VALUE ASSET CONTROL SYSTEM

The high value asset control system (HIVAC) is the result of SecNav Instruction 4440.29 (Series). This instruction prescribes a Navy-wide high value item management program. The purpose of the program is to achieve inventory economies without impairing combat readiness. In the past the military services have been criticized for management deficiencies which led to accumulation of costly excess stocks.

The need for specialized, intensive management attention to a relatively small percentage of items can be better understood when considering the ever-increasing costs of weapon system and the increase in the costs of the major supporting spares and components for these systems. These costs have had an impact on the national economy approaching that of military expenditures of World War II.

By using the best techniques in the management of high value items, which represents approximately 40 percent of the annual procurement dollar expenditure, inventories and procurement investments can be reduced considerably and still maintain an acceptable level of readiness.

High value items, as described in NavSup Instruction 4440.105 (Series), are identified by a specific material control (fraction) code on all supply documents as follows: Repairable items with a unit cost of $1,000 or more are assigned Material Code "G". Consumable items with a unit cost of $1,000 or more are assigned Material Code "J". There are control codes assigned to items other than those mentioned, but these two require worldwide movement accounting.

Although the technician is not directly involved in the program, he is involved at fleet level in that some of these items will be installed in aircraft or held in rotatable pools for which he may be required to assume responsibility. The major responsibility of fleet personnel is supply discipline, since supply discipline in the fleet is an especially critical aspect of the high value program. This is because of the greater difficulty of maintaining accountability under the pressure of operating conditions. Also, prompt action on the part of fleet personnel to expedite handling of high value items is essential to the program. For complete and detailed information concerning the HIVAC system, refer to the instructions previously mentioned in this section.

SURVEYING ACCOUNTABLE MATERIAL

When property must be reevaluated or expended from the records due to loss, damage,

deterioration, or normal wear, a survey must be made to obtain proper authority to write this material off the books. The survey request, Form 154 provides a record showing the cause, condition, responsibility, recommendation for disposition, and authority to expend material from the records. Think of a survey as being an administrative examination into the cause of material being lost to use.

A survey may be either informal or formal, depending on the circumstances.

A formal survey is required for those classes of materials or articles so designated by the bureaus, commands, of offices concerned, or when specifically directed by the commanding officer. A formal survey is made by either a commissioned officer or a board of three officers. At least one of the board members must be a commissioned officer. The commanding officer appoints those who serve on the survey. Neither commanding officer, the officer on whose records the material being surveyed is carried, nor the officer charged with the custody of the material being surveyed, may serve on a survey board.

An informal survey is made by the head of the department having custody of the material to be surveyed. Informal surveys are used in all cases when a formal survey is not required or directed by the comanding officer.

Preparation of Request for Survey

You will not have the responsibility of preparing final survey forms; however, as a first class or chief, you are apt to be required to provide your division officer with certain information when he is making survey. Because of this, you should be familiar with the general procedures that are followed.

A request for survey may be originated by a department, division, or section head or a designated subordinate as prescribed by local regulations. Normally, requests for survey are originated in the department having custody of the material being surveyed. The initial survey request is made on a rough copy of S. and A. Form 154. A statement by the originator is placed on or attached to the request for survey relative to the condition of material; cause of condition surrounding the loss, damage, deterioration, or obsolescence of material; responsibility for cause or condition of material or reason why responsibility cannot be determined; and recommended disposition of material or action to be taken.

Upon receipt of the rough copy, the designated group or section prepares a sufficient number of smooth copies of the request for distribution in accordance with local regulations. The smooth survey request is filled out down to the caption Report. It is then forwarded to the commanding officer who will determine whether the survey will be formal or informal. If formal, the survey request is forwarded to the designated surveying officer(s); if informal, it is forwarded to the head of a department for survey action.

The statement by the originator as to cause, condition, etc., is attached to the smooth request for survey for evaluation by the surveying officer(s). After the survey has been completed by the head of a department or surveying officer(s), it is returned to the commanding officer for review and action. After approval by the commanding officer, the survey request is forwarded to the cognizant command for final review and approval when so required.

USE OF PUBLICATIONS

As a First Class or Chief Aviation Electrician's Mate, your responsibilities in connection with installing, adjusting, maintaining, and testing electrical equipment will be much greater than they were when you were a lower rated petty officer. You will be required to have quick and accurate answers to many questions. Since there is a wide variety of complex equipment, you cannot expect to have a ready answer to all questions. However, you can become familiar with the published materials that contain the answers, and by so doing you will be able to take positive action.

MAINTENANCE INSTRUCTIONS MANUAL

A Maintenance Instructions Manual (formerly called Handbook of Maintenance Instructions) is developed for each of the newer models of aircraft. Recent manuals are issued with the sections as separate volumes to facilitate the use of the manual by the different shops. The sections concerning electric and electronic systems maintenance and wiring data are of prime interest to the AE.

Location of components and instructions for removal and installation are included in the

manual. The wiring diagrams, power distribution charts, and drawings showing the location and connection of fuses and circuit breakers are valuable to the electrician while troubleshooting in the aircraft.

Information on electronic equipment maintenance is also included. The amount of this information or the depth of maintenance discussed will vary from one manual to another and also between equipments within a given manual. Included in some manuals for organization maintenance are operational and functional checks, trouble isolation charts, and adjustment charts. The intermediate maintenance section may contain information for bench checks, troubleshooting, disassembly, repair and parts replacement, and assembly instructions. If special support equipment is needed to accomplish the maintenance described, a section on use and maintenance of this support equipment may be found in the volume on electronic maintenance.

These manuals, when used in conjunction with the Service Instruction Manual for the electronic equipment, furnish the technician with information needed to properly maintain the equipment.

OPERATION AND SERVICE INSTRUCTION MANUALS

The Naval Air Systems Command procures Operation and Service Instruction Manuals (formerly called Handbook of Operating Instructions and Handbook of Service Instructions) for various avionics equipments. The Operation and Service Instruction Manuals may be issued as one combined manual or as separate manuals. In some cases, where the equipment is installed in only one type aircraft, the Maintenance Instructions Manual for that aircraft will contain the information normally found in the Operation and Service Instruction Manuals. Aviation Electrician's Mate 3 & 2, NavPers 10348-C, chapter 23, lists the subject content of each section of this manual. The discussion in this course will be limited to a few of the items contained in the manual.

Performance Specfications

As a senior AE, your responsibilities for inspecting the work of others will increase. The Operation and Service Instruction Manual contains charts or sections on standards which the equipment should meet if it is to be considered as performing satisfactorily. The use of this information to determine the quality of your own work or the work of some other AE is recommended. The preflight checks given in the manual usually provide only an indication of overall system operation and do not indicate how much above minimum standards each section is operating. There are some equipments that utilize line testers for this check; line testers quite frequently are of the GO, NO-GO type. This is the most basic of the performance standards the equipment must meet.

The preliminary or preinstallation inspection is normally a bench test procedure for equipment received from the supply system or from an intermediate maintenance activity. Normally, this is also a check for overall operation of the equipment and is not designed to check the equipment for specific circuit performance.

The portion of the manual that gives the performance standards for the individual sections of the equipment is titled "Minimum Performance Checks" or "Specifications." These standards are shop procedures used to check the individual sections of the equipment against the acceptable performance levels. In addition to listing the minimum acceptable performance levels, this section gives procedures for setting up the equipment for test, the test equipment to use, and the adjustments required to bring the equipment up to standard.

Where the equipment fails to meet minimum performance standards, a malfunction is indicated. Trouble analysis charts and alinement procedures are included in the manual to assist the electrician in locating and correcting the malfunction.

Adjustments

The Operation and Service Instruction Manual contains charts and instructions for adjusting the equipment. One of these charts will be found in the organizational maintenance section of the manual. The information given will concern minor repairs and adjustments.

The adjustments given in the field (intermediate) maintenance section are more extensive than those in the section on organizational maintenance. Normally included in this section are the complete alinement procedures for each section of the equipment. The instructions include the step by step procedures and give the test equipment setup required.

Special Tools

The Operation and Service Instruction Manual furnishes a list of special tools required for maintaining the specific equipment. The electrician should check the applicable allowance list to determine whether the tools are available to his unit as organizational property or if it will be necessary to procure them on custody from the supporting activity.

LETTER TYPE TECHNICAL DIRECTIVES (CHANGES AND BULLETINS)

NavAir Instruction 5215.8 established a system to promote uniformity in technical directives. This system is limited to instructions of a technical nature which are not contained in technical manuals and which cannot be satisfactorily incorporated as revisions to the manuals. NavSup Publication 2002, Cognizance Symbol I, Section VIII, Part D, together with its latest cumulative supplement, provides a checkoff list for all current technical aeronautic letter publications.

A CHANGE is a technical directive containing instructions and directions to accomplish a material change, modification, repositioning, or alteration in the physical appearance of an aircraft or equipment or the installation of different parts in subassemblies, assemblies, or components in aircraft or equipment.

A BULLETIN is a technical directive containing instructions and directions to accomplish inspections, calibrations, tests and adjustments, or additional instructions on standard rework, methods, limitations, and procedures which do not fall within the change definition.

A GENERAL BULLETIN may be used in instances where the instructions and directions apply to a number of different powerplants, airframes, etc.

An INTERIM CHANGE or an INTERIM BULLETIN is a change or bulletin directive in message form which defines the action to be taken to correct a safety or operational condition which embodies risks considered to be in need of immediate correction. Interim directives may or may not contain the final solution to the problem. Interim directives are issued only when the action classification (discussed below is Immediate or Urgent).

Action Classification

The action classification and compliance requirements for completing the directed action are of major concern and importance. In establishing time limits, the originator has considered the type and seriousness of the deficiency, operational employment and environmental conditions affecting the deficiency, prior to accomplishment of other changes, and special tools or facilities required.

IMMEDIATE ACTION.—This type directive is concerned with problems involving safety, which would probably result in fatal or serious injury to personnel, or destruction of (or extensive damage to) property, unless corrected within extremely narrow time limits. Immediate Action directives involve the immediate discontinued use of the aircraft, engine, or equipment in the operational employment under which the adverse safety condition exists. If continued use will not involve the affected component or system in either normal or emergency situations, compliance may be deferred until (but no later than) the next periodic inspection for aircraft and engines, and no later than 6 months from date of issue for equipments.

URGENT ACTION.—A directive of this type also indicates a problem in safety conditions which could result in personnel injury or property damage unless corrected. The major difference is that time limits are not quite so close as with Immediate Action directives, but are still narrow. Operating restrictions may or may not be imposed. (This classification may also be used for mission capability changes when operational and deployment commitments are considered of overriding importance.)

Interim directives classified Urgent Action require incorporation within 60 days from date of issue in those aircraft, engines, or equipments employed under conditions in which the hazard exists. If continued operation will not involve use of the affected component under either normal or emergency situations, action may be deferred up to 180 days from date of issue.

Formal directives classified Urgent Action require incorporation not later than the next Progressive Aircraft Rework (PAR) period or overhaul for aircraft and engines, and 18 months from date of issue for equipments.

ROUTINE ACTION.—These directives indicate conditions which, if uncorrected, could

eventually result in personnel injury or property damage, or could have an adverse effect on operation, maintenance, or support functions. Although a hazard may exist, the situation is not considered to be critical; therefore, action may be deferred not more than one PAR or overhaul for aircraft and engines, and 18 months from date of issue for equipments.

Noncritical changes requiring the facilities of a Naval Industrial Activity could seriously interfere with operational or deployment commitments. In this event, the change may be deferred by the controlling custodian until the next succeeding PAR or overhaul.

Title

Changes and bulletins are issued under title subjects—Airframe, Powerplant, Avionics, Accessory, Support Equipment, Aviation Armament, Air Crew System, Photographic, Clothing & Survival Equipment, Propeller, etc.

Numbering

The number is assigned separately for each type directive and for each title subject, in numerical sequence by date of approval (not necessarily the date of issue). Interim changes and bulletins are numbered in sequence along with formal directives; formal directives issued to supersede interims retain the same sequence number.

Occasionally directives require amendment or revision. A REVISION is a completely new edition of an existing publication, and bears the words "Rev. A" or "Rev. B" as appropriate. An AMENDMENT makes a minor change or addition to the basic directive, and is indicated by "Amendment 1" following the basic title.

Some changes are intended to be installed in stages, or by different level maintenance activities. These changes are issued as "Part I" and "Part II" of the basic directive.

Format

Although there are some slight variations in detail, all letter type technical publications conform generally to a standardized format. Only a few of the topics covered in the directive warrant discussion in this course. They are as follows:

1. Publications affected. List the publications which should be revised as a result of incorporation of the directive.
2. Application. Identifies the specific aircraft, engines, or equipment to which the directive applies.
3. Supply Data. Presents detailed information covering all material and supply transactions involved in support of the directed action.
4. Detailed instructions. For the maintenance technician, this is the most important part of the directive. It presents the detailed step by step procedures to be followed in accomplishing the directed action.
5. Identification. Gives instructions for marking the unit upon completion of the action, for easy identification of those units which have undergone modification.
6. Log entry. Indicates the entry, if any, to be made on the applicable logbook.

Obsolescent Types

Many directives which were issued prior to the standardization of the directives system are still effective. These include Aviation Circular Letters, Technical Orders, Technical Notes, Aircraft Services Changes, Aircraft Service Bulletins, Electronic Material Changes, and Electronic Material Bulletins. Although these directives are no longer being issued, those which have not been canceled or superseded are included in the latest edition of the NavSup 2002, Section VIII, Part D.

Local Action

Upon receipt of a letter type technical directive, either formal or interim, the directive must be screened by the maintenance activity to determine its applicability to units or aircraft maintained by that activity. If local compliance is required, a local maintenance instruction is prepared to direct compliance by shop personnel. This local instruction provides a ready reference to determine the status of action based on that directive in the activity, and provides a record of which units have been processed.

AIRCRAFT INSTRUMENTS AND ACCESSORIES BULLETINS

These bulletins are issued in order that information and changes pertaining to various instruments and accessories may be more readily distributed and made available to the units concerned. They are prepared, issued, and distributed in message or formal format

by the Naval Air Systems Command at irregular intervals, and are numbered consecutively for each year.

The format of both the instruments and accessories bulletins is basically the same. A typical bulletin presents information under the following headings:

1. Subject.
2. Publications Affected.
3. Application.
4. Compliance.
5. Detailed Instructions.
6. Parts Required.
7. Parts Removed.
8. Special Tools Required.
9. Source of Parts.
10. Man-Hours Required.
11. Disposition of Parts Removed.
12. Effect on Weight and Balance.

Many times the nature of the information being presented is such that every major heading need not be utilized. When this is the case, words such as "none," "not applicable," etc., are inserted.

These bulletins can be of much use in presenting new information. An up-to-date file should be maintained and it should be kept in an easily accessible place.

Section VIII, Part D of Navy Stock List of Forms and Publications, NavSup Publication 2002, contains a listing of all current instruments and accessories bulletins. Consult the general alphabetical index, located in the back of the index, for page number references for the listings of the bulletins.

MISCELLANEOUS PUBLICATIONS

There are a great number of technical publications, other than the maintenance and service instructions, that the AE will find useful in performing his job. This section lists and describes briefly a few of these publications. By including this type of publication in the shop technical library, the supervisor will be providing information that should increase the efficiency of the shop.

Basic Theory and Application of Transistors, NavWeps 00-80T-86

This manual is a basic course in the theory of transistors. It begins with an introduction and fundamental theory of transistors and proceeds with technical accuracy with explanations of amplifier fundamentals, bias stabilization, transistor analysis and comparison, audio and tuned amplifiers, wide-band oscillators, pulse and switching circuits, modulation, mixing, and demodulation, and ends with an introduction to additional semiconductor devices.

This manual is especially advantageous to the senior AE who is preparing a program of instruction on this subject for his men. The information is presented in a simplified form so as to allow maximum coverage of information in a unified manner.

The manual is divided into sections. Each section provides test procedures for a specific type of electrical power equipment. A complete test procedure for one basic model is given. The test procedure for the selected model is the most universal for the specific type of equipment. The basic portion of each section contains the following:

1. Description and leading particulars.
2. Typical test values.
3. Preparation for test, including any necessary inspections, checks, or maintenance operations.
4. Detailed step-by-step test procedures.

The sections of the manual are as follows:

1. Introduction.
2. Test procedures for d-c generators.
3. Test procedures for d-c voltage regulators.
4. Test procedures for a-c, d-c generators.
5. Test procedures for a-c generators.
6. Test procedures for a-c voltage regulators.
7. Test procedures for inverters.

Electronic Circuit Analysis, NavAir 00-80T-79, Vols. I and II

This manual is published in two volumes and provides the electrician with reference information on the fundamentals of electronic and electrical circuits. It includes information such as electronics mathematics, d-c and a-c circuits, measuring instruments, transistors, and other electrical and electronic applications.

Reduction of Radio Interference in Aircraft, NavAir 16-1-521

The purpose of this manual is to present information which will serve as a guide to the aviation industry and to naval aircraft maintenance activities for achievement and maintenance of

the lowest practicable level of radio interference in naval aircraft. It may be used as a guide to enable you to determine the type of interference, to locate its source, and to provide a means for its elimination or suppression. The information is presented under the following headings:

1. Purpose.
2. Types and effects of radio interference.
3. Sources of radio interference.
4. Interference coupling.
5. Basic installation planning for radio interference control.
6. Radio interference reduction components; their section, application, and installation.
7. Bonds and bonding.
8. Shields and shielding.
9. Testing for radio interference.
10. Maintenance aspects of radio interference.

Aircraft Electrical Power Equipment, NavAir 17-15BA-500

This is a manual that provides instructions for the use of the standard test equipment that has been manufactured to test aircraft electric power equipment. The test equipment consists of an aircraft generator (drive)-test stand and the aircraft electrical power equipment test assembly.

Department of the Navy Safety Precautions for Shore Activities, NavSop-2455

The purpose of this manual is to present the safety precautions applicable to Navy shore activities including shore (field) activities of the Operating Forces and fleet schools. The safety precautions given in this manual are of necessity basic and general in nature and are not, inclusive of all conceivable operations and functions involved in the great variety of shore activities. In many instances references are made to other publications for detailed safety precautions applicable to specific operations.

The senior AE should become very familiar with the contents of this manual. It is the responsibility of supervisory personnel to see that safety precautions are strictly adhered to. Continuous cooperation and vigilance of all personnel are needed to see that all operating procedures and work methods do not unnecessarily expose personnel to injury or porperty to loss or damage.

Index of Safety Precautions, OpNav Notice 5100

OpNav Notice 5100 is an index of Navy Department documents containing safety precautions applicable to the operating forces.

The manual, "United States Navy Safety Precautions" (OpNav 34P1), is no longer issued for use by the operating forces. To assist commanders in the operating forces in carrying out their responsibilities in the area of safety, the Chief of Naval Operations has revised the index of publications, pamphlets, periodicals, and directives, issued by bureaus and offices of the Navy Department, which address themselves to safety precautions applicable to the operating forces.

The safety precautions listed in OpNav Notice 5100 are not intended to replace the instructions in manuals but only to supplement by providing specific safety precautions in certain categories where they have been changed or have been implemented. When the listed precautions references have been included in manuals, they will be deleted from the index. It behooves the senior AE to review this index and to study sections applicable to his activity. As stated previously, it is the responsibility of supervisory personnel to ascertain that all safety precautions, as cited in OpNav 5100, are rigidly enforced.

FILING AND MAINTAINING PUBLICATIONS

A steady stream of technical correspondence, directives, and publications is received by the Avionics Division. A system for filing this paperwork and disseminating the useful information must be established if full value of these sources is to be realized. In order for the information to be of value to the division, it must be brought to the attention of the personnel in the shop. A routing system within the shop will provide for the dissemination of the information to all personnel concerned. Particular attention must be paid to insuring that TAD personnel are brought up to date periodically and as necessary.

There is a great deal of technical information received concerning the many pieces of equipment. The file location of this information must be known and accessible, so that the individual assigned to repair or test the equipment will have all the necessary information available.

The avionics shop should establish and maintain a technical library in close conjunction with the quality control division. The shop's technical library should consist primarily of a complete and current set of letter publications and technical manuals which are pertinent to equipments and aircraft serviced by the shop. In addition, it should contain a file of the Digest of U.S. Naval Aviation Electronics, NavWeps 08-1-503, and other material of informative or training nature.

The technical library should be kept in an orderly fashion, and its facilities made readily available to all assigned personnel. General and little used material should be filed in the division or shop office, and the manuals should be filed in the shop.

For larger activities, or those where many people utilize the same technical library, it is imperative that a checkout system be instituted for certain publications. This system will enable an interested individual to locate needed publications checked out by other personnel and will also aid in maintaining a complete and current library.

SECURITY OF CLASSIFIED PUBLICATIONS

Security is one of the chief responsibilities confronting the Avionics Division. Although security is the duty and responsibility of all hands, security rests heavily upon supervisors because of the classification of the equipments, systems, and publications with which AE's work.

DEPARTMENT OF THE NAVY SECURITY MANUAL FOR CLASSIFIED INFORMATION

The objective of the orders and instructions contained in this publication is to establish a coordinated policy for the maintenance of the security of all matter classified in the interest of national defense. The United States Navy Regulations, the Espionage Act, the Atomic Energy Act, executive orders, and other legally established directives form the basis for this publication. These regulations do not restrict the mature judgment of individuals in the proper application of initiative, and local commands may issue additional security instructions as necessary to meet local situations. However, this manual contains detailed procedures and outlines basic responsibilities of the security system. Reference to this manual will provide methods of implementation of the security system for most circumstances likely to be encountered. The senior AE should be familiar with this publication.

SECURITY RESPONSIBILITY

Commanding officers are directly responsible for safeguarding all classified matter within their commands and are responsible for instructing their personnel in security practices and procedures.

Security consciousness is the duty and responsibility of all Naval personnel, but especially is this true of avionics personnel. All avionics personnel should be security conscious, and that consciousness should be maintained by repeated instructions in matters of security.

HANDLING AND STOWAGE

Handling and stowage procedures concerning classified publications are dependent upon both the classification and the quantities of the particular material to be stored. However, rarely should the Avionics Division maintain permanent custody of any publications classified Top Secret or Secret. If such custody is necessary, strict attention to instructions for handling and stowage of Top Secret and Secret material should be observed.

A checkout system utilizing logbooks or custody cards must be maintained for the proper handling of classified publications.

KEYS AND COMBINATIONS

It is essential that combinations or keys be accessible only to those personnel whose official duties demand access to the container involved. The combination to a security container should be changed whenever any one of the following conditions occurs:

1. When the combination lock is received.
2. When a person having knowledge of the combination leaves the organizational unit.
3. When there is reason to believe the combination has been compromised.
4. When the lock has not been changed in a 12-month period.

PERSONNEL SECURITY CLEARANCES

Any person having access to classified matter must have a security clearance. Never assume

the security clearance of anyone, regardless of rank or rating or previous assignments. Always demand valid proof of entitlement to classified information. Limit access to classified information, and to the files, to a "need to know" basis (information necessary for the performance of the individual's duties). On the other hand, remember that AE personnel, due to the nature of their rating and the continual need for updating their education on the latest avionics systems, should be properly cleared and have access to material relevant to the duties of their ratings. Leading petty officers should take the lead in establishing the right balance in this area.

CHAPTER 3
MAINTENANCE TECHNIQUES

The supervision of maintenance on electrical/instrument equipment is a major responsibility of senior AE's. The job of supervision is a many-sided task. Some of the techniques will have been learned through past experience. Others will have to be learned during actual supervision of maintenance. Still other techniques may be learned from self study courses and technical publications.

Three general objectives of shop supervision are listed below and discussed in the following paragraphs. The supervisor may be able to add to this list after a detailed study of his own specific duties and responsibilities. The objectives are as follows:

1. To operate with maximum efficiency and safety.
2. To operate with minimum expense and waste.
3. To operate free from interruption and difficulty.

Operating with maximum efficiency and safety is dependent to a large extent upon how conveniently the workspaces and equipment are arranged in the shop. Making a drastic rearrangement to improve the utilization of a single piece of equipment may not be economically feasible; however, a drastic change which results in improved utilization of several equipments may be worthwhile. The new shop supervisor will want to make an evaluation of the existing shop layout to assure himself that he has the most efficient arrangement possible.

A supervisor should know his men's limitations and capabilities. He should use the capabilities of his best men in a twofold manner. Whenever possible he should assign a well qualified man to do a certain job and add to the team other individuals who are less qualified but who are professionally ready for advanced on-the-job training.

The supervisor must anticipate the eventual loss of his most experienced workers through transfers, discharges, etc., and offset this by the establishment of an effective and continuing training program. In addition to raising the skill level of his division, the training program will insure that qualified personnel will be ready for advancement examinations.

A shop safety program must be organized and administered. Current Navy directives and local policies are quite specific as to the establishment of safety training programs.

The keeping of accurate and complete records is another factor in the efficient operation of a shop. This includes records of usage data, work accomplishment, and personnel progress. The most efficient recordkeeper is one who has enough records without having his files bulging with useless and outdated material.

A knowledge of the principles of man-hour accounting is necessary in the efficient utilization of the manpower available. The supervisor should schedule his workload in such a way that planned absences of key workers will not unduly interrupt the daily routine. When scheduling the workload, he should keep in mind the skill level required for the various tasks and assign individuals to jobs in such a way that the work may still progress if any worker is unexpectedly absent.

Operating with minimum expense and waste is our second objective. The shop supervisor has responsibility for ordering and accounting for aircraft spare parts and material. He must impress upon his men the need for being thrifty in the use of these materials. There are many ways to economize, and the supervisor and his senior petty officers should always be on the alert for opportunities to point out these ways to the less experienced individuals.

Meeting the third objective depends largely upon the availability and condition of tools, test equipment, and maintenance publications. A smoothly functioning shop will have all its equipment in good working order; its tools in good condition, of the proper type, and in sufficient quantity for the number of men assigned; and its maintenance publication file complete with the latest publications covering all equipment and systems that the shop is responsible for maintaining.

The shop functions may be further smoothed by the judicious delegation of authority to

individuals next in seniority to the supervisor. The delegation of authority does not relieve the supervisor of the final responsibility for work accomplishment. It is primarily a means of relieving the supervisor of details. A supervisor who allows himself to become too involved with details loses his effectiveness as a supervisor.

ORGANIZATION OF MAINTENANCE AND REPAIR FACILITIES

As previously stated, the job of a supervisor is a many-sided one. It has a particular importance with respect to the operation of a maintenance and repair facility. The supervisor should fully understand and appreciate the responsibility he holds as a member of the organization. He must be able to identify each of his duties with respect to the mission of the organization, not an easy task in a field as complex and variable as the work of a supervisor.

SHOP LAYOUT

The supervisor's first assignment in shop layout may be either the initial planning for a new repair facility or the modernization and improvement of an existing facility. In either case the supervisor's goal is to utilize space as efficiently as possible.

The following paragraphs discuss some of the areas to be considered when planning shop layout. They are not to be considered as an exhaustive listing of all the problems that will be encountered, or as the only solutions to the problems. They are, however, a representative listing of some of the basic areas to be considered.

Purpose of the Shop

One basic consideration in planning a shop layout is the purpose of the shop. When more than one space is available, the supervisor must decide which shops will occupy the spaces and, if necessary, which will have to share spaces. Of two available areas, for example, one may be unacceptable as an electrical shop if the shape of one of the areas precludes the placement of large items of test equipment. This space, however, may be ideal for the instrument shop.

Where one shop is readily accessible on the hangar deck level and access to another involves climbing a ladder or traveling a considerable distance, the relative size and weight of components would be an important point to consider.

Another factor to consider is the close proximity of rotating or switching devices that might cause interference. This would be more objectionable in its effects on some equipments than on others.

Security of classified matter may be a consideration in determining the usage of the particular spaces. If the amount of classified equipment is such that a separate shop can be efficiently utilized for it, the problem of control of classified publications and material will be greatly reduced.

Bench Arrangement

Following the determination of which shops are to occupy what spaces (or areas within a space), the next problem is the arrangement of test benches and test sets within the shop. Proper placement of test benches and test sets can do much to increase the efficiency of the shop.

The supervisor's first step in planning the arrangement of test benches should be to fully familiarize himself with the power distribution system. Placement and grouping of the particular test sets and equipments can be accomplished only within the limits imposed by the power distribution system. In planning for new installations, the supervisor should utilize the Design Guide for Avionics Shop Power Distribution, NavAir 01-1A-512.

Some test benches and their related equipments have extremely high usage or great inherent danger potential. Placing these away from heavy traffic areas near entrances, offices, or tool issue rooms would be advisable.

Sufficient workspace should be allotted adjacent to the test bench harness for portable test equipment, tools, and for the use of technical publications.

Permanently mounted test equipment and electrical/instrument equipment components (controls, dynamotors, etc.) should be mounted so as to be accessible in a safe and efficient manner.

In an area designated for the disassembly and repair of miniature components consideration should be given to the installation of special lighting.

Another consideration in placing particular test benches is their relationship, desirable or

undesirable, to certain permanently installed items. The location of air outlets, electrical equipment cleaning facilities, machines, or devices that might cause interference, are some of the items to be considered.

If a separate shop is not utilized for classified equipments, then placement of these equipments in a section of the shop where the physical layout lends itself to limiting or controlling access is desirable.

Shop Housekeeping

A clean orderly shop reflects good supervision. The supervisor has the responsibility for originating and publishing cleaning bills and schedules. In setting up the shop job assignments and work schedules, the supervisor must allot time for scheduled cleaning. The availability of sufficient cleaning gear to accomplish the scheduled cleaning is also the responsibility of the supervisor.

Providing proper and adequate stowage space for tools, test equipment, publications, and other materials when not in use can do much to aid in keeping an orderly shop.

In shop housekeeping, as well as other fields of responsibility, the constant search for problems and the timely solution thereof are prime functions of a good supervisor.

CARE OF TOOLS AND TEST EQUIPMENT

The maintenance of electrical/instrument equipment requires a large amount of expensive and delicate test equipment, special tools, and common handtools. The availability of tools and test equipment, in good condition and proper working order, can do much to help meet the work schedule and add to the quality of the work.

Basic Handtools, NavPers 10085-A, contains information on the proper care and use of many tools as well as information on basic skills in using handtools. The instruction manuals supplied with each test equipment contain sections devoted to the proper care of, and proper operating procedures for, that specific equipment and usually for test equipment in general. By utilizing these sources of information, the supervisor can emphasize proper use and care of tools and equipment. This emphasis can be achieved in both safety and technical lectures, but the most effective method is by making proper usage and procedures an inherent part of on-the-job training, job instructions and explanation, and day-to-day supervision.

Applicable allowance lists specify the type and quantity of tools and test equipment that a shop is allowed. The allowance lists should be cross-checked with a current inventory and any deficiencies made up as soon as possible. In some cases, it may be determined that some items on the allowance lists are not needed, or that the allowed quantity exceeds actual requirements. In such cases, those items should not be ordered. Excess items serve to complicate the periodic inventories.

Some items should be kept in the shop tool and test equipment issue room or special cabinet, others should be permanently mounted, and still others should be placed in individual toolboxes and issued to the workers. A toolbox inventory record should be prepared in duplicate with the original filed in the shop files and the duplicate copy placed in the toolbox, preferably in an oil and grease resistant envelope.

A monthly inventory should be conducted beginning with the toolboxes and ending with the issue room count. The periodic inventory should be more than just an item count. Since each item is sighted, it provides an opportunity to ascertain if the items in actual use are being maintained in good repair. If they show evidence of damage or improper use, appropriate corrective action should be taken. The supervisor should allot time in the work schedule for test equipment servicing and tool maintenance.

The loss of or damage to a tool should be noticed during a periodic tool inventory. This may eliminate a work delay which might develop if a required tool were first discovered to be missing or damaged during the progress of a job.

Most items of test equipment and some tools will require a custody record. The supervisor must follow local instructions when accounting for and keeping records on custody and subcustody items.

Programmed calibration of test equipment is handled in accordance with directives issued on the subject by the Naval Air Systems Command.

SAFETY

Operational readiness of the maximum number of aircraft is necessary if naval aviation is to successfully perform its mission. Keeping

aircraft in top operating condition is the principal function of naval aviation maintenance personnel. It is essential that maintenance work be performed without injury to personnel and damage to equipment and aircraft.

Electrical/instrument maintenance is, to some extent, naturally hazardous due to the nature of the work, the equipment and tools involved, and the variety of materials required to perform many repairs and maintenance functions. Factors which can function to increase or decrease these hazards are as follows:

1. The experience levels and mental attitudes of assigned personnel.
2. The quality of supervision of the maintenance tasks.

Thorough indoctrination of all personnel is the most important single step in maintaining safe working conditions.

The concept of maintenance safety should extend beyond concern for injury to ground crew personnel and damage to equipment and aircraft. Safe work habits go hand-in-hand with flying safety. Tools left in aircraft, improper torquing of fasteners, and poor housekeeping around aircraft can cause conditions which may claim the lives of flying personnel. Safety on the ground is equally as important as safety in the air.

It has been stated that "While the increased complexity of our modern aircraft is a factor, it is noted that a large number of maintenance-error-caused accidents and incidents are due, not to complexity of equipment, but to lack of supervision and technical knowledge. Many mistakes are simple ones in routine maintenance."

Safety in aircraft maintenance depends largely upon the supervisory personnel. The standards of quality which they establish and maintain are directly reflected in the quality of the aircraft maintenance. The primary duty of the senior petty officers is to supervise and instruct others rather than to become totally engrossed in actual production. Attempts to perform both functions invariably result in inadequate supervision and greater chance of error. Supervisors must exercise mature judgment when assigning personnel to maintenance jobs. Consideration must be given to each man's experience, training, and ability.

Sometimes overlooked in a maintenance program are the considerations generally grouped under the term "human factors." These factors are important in that they determine if an individual is ready and physically able to do work safely and with quality. Supervisory personnel should be constantly aware of conditions such as general health, physical and mental fatigue, unit and individual morale, training and experience levels of personnel, and other conditions which can contribute to varying degrees to unsafe work. Not only is it important that proper tools and protective clothing and equipment are available for use, but also the insistence by maintenance supervisors that they are used is of utmost importance.

It is a continuing duty of every person connected with aircraft maintenance to try to discover and eliminate unsafe work practices. Accidents which are caused by such practices may not take place until a much later date and their severity cannot be predicted. The consequences may range from simple material failure to a major accident resulting in serious injuries or fatalities.

There are several areas in which the shop supervisor can effectively work to minimize accidents incident to aircraft maintenance. Among these are continuing inspections of work areas, tools, and equipment; organization and administration of safety programs; correct interpretation of safety directives and precautions; and energetic and imaginative enforcement of them.

Inspection of Work Areas, Tools, and Equipment

The supervisor should diligently inspect work areas, tools, and equipment to detect potentially hazardous and unsafe conditions and take appropriate corrective action. The AE may be working in the shop, in the hangar, or on the line, and all these areas should be included in the supervisor's inspection.

Fire and explosion hazards present a serious problem. NO SMOKING rules should be enforced, as should the rules for operating electrical equipments during fueling operations or at other times when it would be hazardous. Ground wires should be used when and where prescribed. Spilled oil, grease, and chemicals should be wiped up immediately and the rags used should be discarded in covered metal containers.

Handtools should be in good condition, of the proper type, and used only for the purpose for which they were intended. Basic Handtools,

NavPers 10085-A, provides extensive coverage on safe use and care of handtools.

Insure that equipment is used only by qualified personnel, and that all safety devices and guards are installed, in good condition, and used in the prescribed manner.

Electrical maintenance personnel will frequently encounter dangerously high voltages, and adherence to all electrical safety precautions must be required of all personnel. Refer to chapter 1 of Basic Electricity, NavPers 10086-B, and chapter 2 of Aviation Electrician's Mate 3 & 2, NavPers 10348-C for specific electrical safety precautions.

By frequent inspections of work areas the supervisor can discover unsafe work habits of assigned personnel as well as unsafe conditions that exist. This is important since some young and inexperienced personnel in their concern for optimum functioning of equipments, may neglect the safety warnings found in the manuals for the equipments.

Organization and Administration of Safety Programs

The safety program for electrical maintenance personnel should be conducted with the purpose of making each electrician an electrical safety specialist, trained to recognize and correct unsafe conditions whenever they may occur. Spasmodic drives on accidents cannot substitute for adequate training, as they tend to be quickly forgotten; new situations arise every day and bring new dangers. Work methods which do not expose personnel unnecessarily to injury or occupational health hazards must be adopted. Instruction in appropriate safety precautions is required, and disciplinary action should be taken in cases of willful violations.

The shop safety program will generally involve three areas of attention—the posting of the most important safety precautions in appropriate places, the incorporation of safety lessons in the formal training program, and frequent checks for understanding during the day-to-day supervision of work.

Posted safety precautions are more effective if they may be easily complied with. For example, a sign in the battery shop requiring use of goggles and gloves when handling batteries, could also point out the location of the gloves and goggles.

Fixed posters and signs should be renewed frequently and not allowed to become rusty, faded, or covered with dust and dirt. General safety posters on bulletin boards and other places should be rotated often to stimulate interest. Appropriate safety posters may be obtained from the squadron or unit safety officer.

The formal safety training sessions should utilize films, books, visual aids, or any other suitable technical material. The men should be told more than just what to do, or what not to do. Each safety subject should be explained in detail. The results of unsafe acts are usually dramatic and easily remembered. Causes of accidents and contributing factors should be reviewed and analyzed. Many good ideas for accident prevention have been developed in training sessions devoted to such analysis.

An extensive series of lessons may be developed over a period of time as latent hazards are recognized, and this will aid in keeping the sessions interesting while avoiding too frequent repetition.

It may be well to mention the new man in the shop at this point. A separate safety indoctrination lesson which covers all the major hazards of the shop should be given the new man as soon as he reports for work. No supervisor with an effective safety program and an excellent shop safety record wants to take the chance that the new man will be hurt before attending the complete series of safety lessons.

In the third area of safety program administration—followup, the supervisor will do well to delegate authority to his subordinate petty officers to assist him in monitoring the program. The attitude of subordinate petty officers toward safety regulations is important. The junior petty officers should respond more readily to the safety program when given responsibilities in the training of new men than when the plea for observance of safety precautions is made solely on the basis of their personal protection.

Also included in the followup area is a responsibility of the shop supervisor to inquire as quickly and thoroughly as possible into the circumstances of accidents and reports of unsafe practices, and to take corrective action or make recommendations to competent authority.

Interpretation of Safety Directives and Precautions

The items in the various safety directives and publications are designed to cover usual conditions in naval activities. Commanding officers and others in authority are authorized

and encouraged to issue special precautions to their commands to cover local conditions and unusual circumstances. The shop supervisor must include both of these in the administration of his shop safety program.

Safety directives and precautions should be followed to the letter in their specific application. Should any occasion arise in which any doubt exists as to the application of a particular directive or precaution, the measures to be taken are those which will achieve maximum safety.

When new safety posters or precautions are posted, it is the responsibility of the shop supervisor to correctly interpret their application to his men. In this way he will be able to achieve a unity of thought and action in the observance of the required safety rule.

The organization's safety officer is available to assist in interpreting and suggesting ways of implementing various safety directives and precautions.

TRAINING PROGRAM

The Navy places great emphasis on effective and continuous training. As a supervisor you will have a regular and continuing responsibility for the training of others. An efficient training program will do much to alleviate the loss when experienced and highly skilled personnel are transferred.

The organization's operational readiness depends largely on the capability of the maintenance department. In turn, an important part of the maintenance department's work is performed by the Aviation Electrician's Mate. Consequently, the quality and scope of your training program have a real effect on the organization's effectiveness.

The senior petty officer, as a supervisor, must be able to organize and conduct an efficient shop training program.

Organizing a Shop Training Program

The first phase in organizing a training program should be to determine its objectives. On the shop level, these objectives should be as follows:

1. Training of men on subjects of a general nature as specified by the Manual of Qualifications for Advancement, NavPers 18068 (Series). This training is intended primarily to aid the men in rate advancement.

2. Training of men on specialized subjects; namely, the circuits and equipment used in the squadron aircraft. This training is intended primarily to improve their daily working proficiency, and this is generally of more direct benefit to the squadron than rate-advancement training.

The second phase in developing a training program includes a considerable number of steps. The most important of these are as follows:

1. Evaluate each man to be instructed, for the purpose of determining the starting level of the subject matter. For instance, if one or more of the men have never attended a service school, he must be instructed at the basic level of fundamental electricity.

2. List the subjects to be taught. The inclusion of a number of the items on this list will be dictated by the Manual of Qualifications for Advancement, NavPers 18068 (Series). These will be general subjects, a very few of which are electron theory, Ohm's law, capacitive and inductive characteristics, and fundamental transformer theory. The remainder of the list will be made up of specialized items pertaining only to the particular squadron's aircraft.

3. Search out reference books or publications which cover all the items of the foregoing list. NavPers 10052, Training Publications for Advancement, is useful in this connection. At this same time, the subjects should be arranged in the most logical sequence for teaching.

4. Prepare a lesson plan for each subject. When the lesson plans are completed, they will have to be approved by the maintenance officer, because he is officially responsible for the contents of such training programs.

5. Procure space for carrying out the lecture type portion of the program. This will usually be in the electrical shop. However, if other space is available, such features as possible seating arrangements, ventilation, lighting, and outside noise levels should be considered in selecting the proper place.

TRAINING METHODS.—Training methods cover a large field, which is a course of study in itself. A closer and more detailed study of this field is made in the Manual for Navy Instructors, NavPers 16103-C. Also, the Military Requirements training manuals, NavPers 10054-B, 10056-B, and 10057-B, contain information on training.

Only the simplest methods of training are mentioned here, but these should be sufficient

for informal shop-level instruction. The first lesson in the training program should deal with electrical fundamentals. These serve to prepare the men for the subsequent teaching of specialized equipment. Fundamentals will be taught mostly by lecturing and using a chalkboard to illustrate important points. The instructor must keep in mind during this stage that he is teaching general principles and terms which will be used verbatim when he teaches specific circuits later on; that is, the instructor must cover such fundamentals as electromagnetism and magnetic amplifiers so thoroughly that no question as to their operating principles will arise when they are later encountered in equipment.

The teaching of fundamentals on the shop level is more difficult than at service schools, because the instructor probably will not have the means to make demonstrations, or to set up lab problems.

At its best, classroom instruction is limited in effect. Useful and practical knowledge is gained by the trainees when they apply fundamental and theoretical teachings to actual equipment. When commencing instruction on specialized squadron aircraft equipment, the training methods must be changed somewhat. These changes will involve breaking each lesson into four steps when teaching equipment. These steps are as follows:

1. Extensive circuit theory and unit function, referencing the appropriate Service Instruction Manual.
2. Operation and observation of the equipment in action, performed by the trainees at the aircraft, under supervision.
3. Making calibration or adjustment, done only when such adjustment is actually needed, and under supervision.
4. Signal tracing, trouble isolation, and parts replacement, done when actually needed, and under supervision.

Each equipment lesson should deal with only one circuit or set at a time, and as many of the foregoing four steps as possible should be carried out in turn. In most cases only steps 1 and 2 will be carried out as routine instruction. Then, when a discrepancy report on a circuit which has been taught through steps 1 and 2 is received, one or more of the trainees may accompany an experienced supervisor to the aircraft and carry out steps 3 and 4. This method of training is thus seen to serve a dual purpose; trains the men to do a job (the second time without direct supervision), and also routine maintenance work is accomplished.

TRAINING MATERIALS AND AIDS.—There will be a limited number of training materials used in a shop level training program. It may not be practical to build visual aids such as mockups and models, as is done in service schools. The list of materials for the trainees probably will include only note pads, pencils, and as many study texts as can be procured from various sources. The instructor's essential materials will include lesson plans, training records, a chalkboard, and chalk. The required materials will depend mostly on each individual situation. For instance, if a squadron is constantly moving, the chalkboard should be portable, and should fit in a cruise box. For teaching at a shore activity, the chalkboard could be larger and permanently attached to a bulkhead.

An effective shop training program may be further enhanced by the use of training aids. The supervisor should always be on the alert for material that can be utilized as training aids. He must be aware of the existence of applicable training films and, if they are available, schedule them for showing in conjunction with specific lessons.

Types of Training

SCHEDULED TRAINING.—Prepare flexible training schedules. In case of bad weather, operational commitments, and other unit demands, it can be revised as necessary. However, when the time of day and the day of the week have been fixed and the schedule does not have to be changed for one of the reasons listed above, adhere to the schedule.

NONSCHEDULED TRAINING.—This consists mostly of on-the-job training. On-the-job training is predicated upon the system of learning by doing. This system employs a small class comprising an experienced electrician (instructor), and a striker or strikers (trainees), who work together to correct deficiencies in particular equipments. This type of training has a dual advantage in that the necessary maintenance is accomplished along with the required training. The instructor explains clearly the complete procedure he is following while performing the maintenance, and questions the trainee throughout the procedure. Thus he is able to instruct and to determine the trainee's progress. The instructor will gain in experience,

confidence, and leadership. There should be a complete record kept of all on-the-job training.

TRAINING RECORDS.—From the foregoing, it is apparent that different men may become trained to different levels on different equipment. This is true because some may miss lessons at times. There is also the probability of personnel turnover. Obviously, you must see that a training record is carefully kept on each man, with an entry made each time he has undergone instruction.

SPECIALIZED MAINTENANCE TRAINING.—The supervisor can do much to improve the performance level of his men by maximum utilization of the specialized maintenance training that is available. This includes Naval Air Maintenance Training Group units, C-type schools, etc.

The Naval Air Maintenance Training Group offers courses on aircraft and systems. Units of this group are located at most of the major naval air stations.

Naval Air Rework Facilities offer courses on repair of certain electrical/instrument equipments. These, as well as other C-type courses, provide the supervisor with a source of specialized formal training that the men may attend on a returnable basis.

In addition to utilizing the schools mentioned above, the quality of maintenance training can be enhanced by utilizing the assistance offered by Naval Aviation Engineering Service Unit engineers in the training program.

SUPERVISION OF REPAIR WORK

One of the most important duties of a senior AE is that of supervising repair work. The electrical/instrument supervisor is responsible for the electrical/instrument work that is performed on the line as well as that performed in the shop.

One of the most important aids in supervision is a job plan. When setting up a job plan, consider these questions:

1. What is the job?
2. How can it be accomplished?
3. How many men are required?
4. What tools and materials are necessary?

Detailed responsibilities of the electrical/instrument shop supervisor include analysis of reported discrepancies, scheduling, job priority, assignment of personnel, checking work in progress, and inspecting completed work.

ANALYZING DISCREPANCIES

Knowledge of the causes of previous discrepancies plays an important role in the evaluation of newly reported discrepancies. If equipment history records are available, they may contain valuable clues concerning the past performance of the particular equipment undergoing analysis.

The use of discrepancy reports of the types discussed in chapter 2 of this manual may also be helpful. Copies of these reports are normally held in the squadron supply office and in the supply office of the local maintenance activity.

Another source of help in analyzing discrepancies is the Digest of U.S. Naval Aviation Weapons Systems Avionics Edition NavAir 08-1-503. This publication contains detailed information on discrepancy trends for specific equipments, compiled from analyses of many reports from numerous maintenance activities. Also available in the Digest is information describing corrective action taken by various maintenance activities.

JOB PRIORITY AND SCHEDULING

Determining which jobs should be performed first is one of the major responsibilities of the supervisor. This is an important phase of the work, for these decisions determine the use of facilities—men, material, and machinery. Routine work presents no particular problem to a well organized shop, but rush jobs can cause much confusion unless they have been thought through and steps have been taken to see that the work follows well founded principles.

When scheduling work, insure (if practical) that the men or crews will be working on different types of jobs. If a number of men or crews are assigned to the same type jobs there may be an overdemand for certain test equipment, tools, and workspace. This often results in confusion and loss of time.

It is also important to schedule activities so that work is accomplished in the proper sequence. This is especially important if you have men working on different phases of the same job.

Future job assignments should be included in the work schedule so that time will be allotted to accomplish them. This may make it necessary to rearrange the present work schedule to

insure that special jobs will not interfere with the accomplishment of routine work.

ASSIGNMENT OF PERSONNEL

In distributing work, be fair to all the men. It is a natural inclination, and a part of every person's makeup, to give the breaks to the people he likes. The important thing is to realize that you have this inclination and to control it.

Avoid having a man do all the work of one type just because he happens to be an expert in that particular phase of the work. Pass the work around so that each man has an opportunity to develop his skill in all phases of an electrician's job. Assign strikers to assist with various kinds of work so they will gain experience on all kinds of jobs.

Rotating assignments makes the work more interesting for the men and, in addition, better qualifies them for advancement in rating. Another good reason for rotating assignments is that if one highly skilled man does all the work of a certain type, the shop will be at a great disadvantage should he ever leave the crew.

The man who is going to do the repair job may require detailed instructions on how the job is to be performed. The senior AE should be careful to see that the man fully understands what he is going to do, so as to prevent any mistakes due to misunderstanding of instructions. The amount of instruction depends upon the knowledge and experience of the man concerned. If he is an experienced rated man, it may only be necessary to tell him what repairs must be accomplished. Inexperienced men will need additional instructions on what test equipment to use, and the proper procedure to follow. Men should understand that they are free to ask questions in case they are in doubt about any details in doing their assigned work.

In addition to giving instructions on how a job should be accomplished, it is also advisable to be sure the worker understands the importance of the job, the origin of the job, and the part that each person will play in accomplishing the work. In general, men are interested in why a job is necessary and how it is to be accomplished, and will usually turn out better work when they have a clear picture of the total job.

CHECKING PROGRESS OF WORK

The assignment of work is only the first step in processing a job. The AE who is in charge must know his men. He should have a fairly good idea of each man's skill and ability, as well as each man's knowledge regarding the operation of equipment and the accomplishment of repair work.

The best way in which the AE supervisor can obtain this knowledge is to make frequent inspections and check the progress of work being performed. In that way, he will have a good idea as to which jobs, or which men, will require the most supervising.

When checking on the progress of work, the senior AE should be sure that the men are observing proper safety precautions in regard to themselves and the equipment they are operating. In addition, he should see that each man is using the proper tools, and note the quality of work being performed.

In case of any doubt, the supervisor should check to see that the men understand his instructions properly and are doing the work correctly. If necessary, he should provide additional instructions to give a better understanding of the job, or to improve workmanship. By frequently talking to the men and answering their questions, the supervisor can prevent work and material from being wasted, as could be the case if he were not available to give the correct details.

Complications may develop on some repairs which may require additional planning and revised repair procedures. By observing the progress of the various jobs, and whether any are ahead or behind the planned schedule, the supervisor will be able to change the schedule in order to prevent "bottlenecks."

INSPECTING COMPLETED WORK

When a job has been completed, the senior AE in charge should inspect and approve the work. Inspection is necessary to insure that the repair job or the replacement parts will be satisfactory. Inspection of repaired equipment and replacement parts may be accomplished either visually or by means of measuring instruments. In addition, tests are performed to check the condition of repaired equipment.

The supervisor is responsible for determining whether the repair job, including replacement parts, meets the following standards:

1. Have the repaired parts been correctly installed in accordance with instructions?

2. Is the repaired item or replacement part free from defects in material and workmanship?

3. Have all parts or accessories to the repaired equipment been replaced or reinstalled correctly?

4. Has the proper replacement part been used in making repairs?

5. Has the part or item been properly checked and certified ready for service?

The existence of a properly functioning quality assurance division in no way decreases the responsibility of the shop supervisor for the quality of work accomplished. Since the work was performed by shop personnel under the direct supervision of the senior AE, the quality of the work is fundamentally a shop responsibility.

Flight Test

Airborne electrical/instrument equipments are thoroughly checked after repairs, both in the shop and on ground test after reinstallation in the aircraft. However, some types of repairs are not considered complete until the equipment's performance is proved in actual flight.

The requirement for a test flight is a determination which is made by the maintenance officer, and is based on the scope of the work accomplished and its effect on safety and reliability of operation.

Test flight checklists should be properly completed and, at the termination of the flight, returned to the maintenance department.

The test flight list should contain a list of test flight requirements as set forth in the Periodic Maintenance Requirements Manual.

The test flight checklist must be prepared in sets of cards. Detailed instructions for preparing test flight checklists are contained in MIL-M-23618A (WEP).

Test flight checklists contain provisions for the following:

1. Listing pertinent items or aircraft systems to be considered during test flights.
2. Recording required instrument indications.
3. Indicating satisfactory or unsatisfactory performance of all listed items.
4. Detailed comments and recommendations concerning the flight.

MAINTENANCE PROCEDURES

Performance testing data, along with other maintenance information, is covered in the Maintenance Instruction Manual for each particular electrical/instrument equipment. This information has been written to enable the electrician to make an intelligent evaluation of the operating capabilities of that equipment; at the same time, the data serve as a gage for the measurement of equipment efficiency. The standards are designed to insure that equipments operate at maximum efficiency at all times, and to reveal any change from this optimum performance, thus indicating the need for corrective measures.

The information presented in these manuals gives the electrician a step-by-step performance check with all the test connections and test equipment clearly indicated for each step. Performance testing is discussed to show the relationship between that type of testing and preventive maintenance, as a means of emphasizing that the final results may indicate the need for corrective maintenance. Both preventive maintenance and corrective maintenance are discussed in the following paragraphs. Troubleshooting—considered as the principal form of corrective maintenance—is analyzed in detail.

PREVENTIVE MAINTENANCE

The best maintenance work is preventive in nature, potential failures being detected and corrected before they have a chance to develop. Preventive maintenance is defined as those measures taken periodically, or when needed, to achieve maximum efficiency in performance, to insure continuity of service, and to lengthen the useful life of the equipment or system. This form of maintenance consists principally of cleaning, lubrication, and periodic inspections aimed at discovering conditions which, if not corrected, may lead to malfunctions requiring major repair.

Inspections and Tests

Inspections fall into two main categories. First, there is the regular visual inspection of the mechanical aspects of the equipments. This is conducted for the purpose of finding dirt, corrosion, loose connections, mechanical defects, and other sources of trouble. Second, there are functional inspections that are accomplished through periodic tests and through less-frequent bench tests. To realize the most effective results from the regular functional

inspections, a careful record of the performance data on each equipment must be kept.

The value of performance data records is demonstrated in a number of ways. Comparison of data taken on a particular equipment at different times reveals any slow, progressive drifts that may be too small to show up significantly in any one test. While the week-to-week changes may be slight, they should be followed carefully so that necessary replacements or repairs may be made before the margin of performance limits is reached. Any marked variations should be regarded as abnormal, and should be investigated immediately. Another advantage in keeping systematic records of performance and servicing data is that maintenance personnel develop a more rapid familiarization with the equipment involved. The accumulated experience contained in the records furnishes a guide to swift and accurate troubleshooting.

The actual work of testing and servicing, as well as that of recording performance data, should be done systematically. While a logical sequence of steps is required, this does not imply the rigid necessity of making only a step-by-step progression. Working within the overall pattern of procedure, maintenance personnel should analyze the results obtained to eliminate unnecessary steps.

CORRECTIVE MAINTENANCE

Corrective maintenance consists of the location and correction of troubles whenever an equipment or system fails to function properly. Location of the trouble includes the activities of evaluating reported discrepancies and troubleshooting.

The trouble may be corrected by mechanical or electrical adjustments, or it may be necessary to replace one or more parts.

Evaluation of Reported Discrepancies

When a discrepancy is turned in either by crew debriefing or on a "gripe sheet," the first thing to determine is whether the system or equipment is actually faulty. A mistake, often made, is removing the equipment from the aircraft before checking it.

The senior AE should have a prescribed procedure for electricians to follow in checking a discrepancy on equipment installed in an aircraft. Some suggested procedures that will aid in evaluating discrepancies are as follows:

1. Visual inspection. A visual inspection of the equipment in the aircraft may disclose frayed or broken wiring, loose connections (electrical and mechanical), or open circuit protectors, which could cause the malfunction.
2. Operational check. An operational check of the system can aid in analyzing the discrepancies and pinpointing the trouble to a particular unit. In some cases, it may disclose improper operating procedures—especially with newer type equipment or new personnel.
3. Performance checks. The use of portable test equipment, built-in meters, and special test equipment installed in some types of aircraft, will aid in making a performance test of the system in the aircraft. Performance testing, mentioned in the first part of this chapter, should be of great help in localizing the discrepancy to a particular unit which can be removed from the aircraft for repair, or in some cases, repaired in the aircraft.
4. Quality assurance inspections. Highly qualified senior electricians should be provided to conduct thorough inspections on all equipments prior to their installation in the aircraft. This quality control inspection should be a combination of the visual inspection, operational check, and performance check. This inspection will ascertain that each equipment is in proper operating order and completely mission ready.

Troubleshooting

Corrective maintenance is, for the most part, concerned with troubleshooting, which can be further divided into two phases. The first phase is system troubleshooting. It is based on the starting procedure, and is designed to locate the unit in which the trouble exists.

The second phase is unit troubleshooting, and is designed to locate the trouble in the unit in which it occurs. In rare cases it is possible to determine which unit is at fault without following the system troubleshooting method to isolate the unit. However, most of the time it is impossible to determine which unit is at fault until the system method has been employed in whole or in part.

TROUBLE ISOLATION.—When abnormal operation has been traced to a particular stage or to a functionally related group of stages, its cause must be further isolated and identified as due to a particular faulty component or group of components. To do this it may be necessary to disassemble the equipment, either in whole

or in part. After disassembly, the trouble may be immediately apparent through a mere visual inspection, whereupon the trouble should be corrected by repair or replacement.

If the trouble is not immediately apparent, a more detailed procedure should be followed to isolate and repair or replace the actual circuit component responsible for the failure. This procedure consists of tube checks, voltage and resistance checks, waveform analysis, and finally, repair or replacement of the defective component.

Supervisory personnel should insure that detailed trouble isolation procedures are in accordance with the applicable current Service Instruction Manual for the equipment being repaired.

TUBE TESTING.—Electron-tube failures are responsible for the largest percentage of troubles that occur in equipment or systems. However, if a particular system uses a great number of tubes, it is obviously impractical, and not good policy, for an electrician to attempt to locate faults by general tube checking. Only when the fault has been traced to a particular stage should any tubes be tested, and then only those associated with the improperly functioning circuits.

When replacing a tube in a circuit, the electrician should note and record the positions of the equipment controls before changing the setting of any of them. If adjusting the controls with the new tube in place does not correct the abnormal condition, the controls should be returned to their original positions. Unless a reliable tube tester shows the original tube to be defective, the old tube should be returned to the original circuit.

After placing a new tube in a circuit, the electrician must decide whether or not to discard the old tube. Certain types of tubes have applicabilities over a wide range of frequencies and driving voltages, so that their poor performance in one circuit does not necessarily preclude their use in another less demanding circuit.

If a bin of used tubes is kept, each tube should be carefully labeled with a tag showing from what circuit the tube was removed, thus avoiding attempted reuse of the tube in the same type circuit. The tag should also indicate the operating conditions under which the tube "failed."

VOLTAGE MEASUREMENTS.—Since most troubles encountered in equipments and systems either result from abnormal voltage or produce abnormal voltages, voltage measurements are considered an indispensable aid in locating troubles. Testing techniques that utilize voltage measurements also have the advantage that circuit operation is not interrupted. Point-to-point voltage measurement charts which contain the normal operating voltages encountered in the various stages of the equipment are available to the electrician. These voltages are usually measured between the indicated points and ground unless otherwise stated.

When voltage measurements are taken, it is considered good practice to set the voltmeter on the highest range initially so that any excessive voltage in a circuit will not damage the meter. To obtain increased accuracy, the voltmeter may then be set to the designated range for the proper comparison with the representative value given in the voltage charts.

If the internal resistance of the voltmeter and multiplier is approximately comparable in value to the resistance of the circuit under test, it will indicate a considerable lower voltage than the actual voltage present when the meter is removed from the circuit. The sensitivity (in ohms-per-volt) of the voltmeter used to prepare the voltage chart is always given on the charts. Therefore, if a meter of a similar sensitivity is available, it should be used so that the effects of loading will not have to be considered.

When checking voltages, it is important to remember that a voltage reading can be obtained across a resistance, even if the resistance is open. The resistance of the meter and the multipliers forms a circuit resistance when the meter prods are placed across the open resistance. Thus the voltage across the component may appear to be normal when the meter is connected, and abnormal when it is disconnected. If the voltages appear normal on a faulty stage, the next step would be to perform a resistance check of that stage.

NOTE: Certain precautions are presented in Basic Electricity, NavPers 10086-B, as general safety measures pertinent to the measurement of voltages. Supervisors should ascertain that these precautions are adhered to by all personnel who are responsible for the maintenance of electrical/instrument equipment.

RESISTANCE MEASUREMENTS.—Defective components can usually be quickly located by measurement of the d-c resistance between various points in the circuit and a reference

point or points (usually ground). This is true because a fault will generally produce a change in resistance values. Point-to-point resistance charts can be used advantageously at this time. The values given, unless otherwise stated, are measured between the indicated points and ground.

Before making resistance measurements, the electrician should make sure that the power to the equipment under test has been turned off. Since an ohmmeter is essentially a low-range voltmeter and a battery, an ohmmeter connected to a circuit which already has voltages in it may be seriously harmed. The pointer may be deflected off-scale, and the meter movement may be permanently damaged.

Filter capacitors must be discharged before making resistance measurements. This is extremely important when testing power supplies that are disconnected from their loads. If a capacitor discharges through the meter, the surge may burn out the meter movement. Furthermore, contact with a circuit containing a charged capacitor may endanger the life of the person making the test.

WAVEFORM COMPARISON.—The measurement and comparison of waveforms are considered to be very important parts of the circuit analysis used in troubleshooting. In some circuits (for example, pulse circuits), waveform analysis is indispensable. Waveforms may be observed at test points, shown in the waveform charts which are part of the maintenance literature for the equipment. It should be noted that the waveforms given in the instruction books are often idealized and do not show some of the details which are normally present when the actual waveform is displayed on an oscilloscope.

By comparing the observed waveform with the reference waveform, faults can be localized rapidly. A departure from the normal waveform indicates a fault that is located between the point where the waveform is last seen to be normal and the point where it is observed to be abnormal. (For example, if a waveform is observed to be normal at the grid circuit and abnormal at the plate circuit of the same stage, this indicates that the trouble lies in that stage or possibly the input of the following stage.)

When waveforms associated with a multivibrator, such as the gunfiring interlock, or a similar circuit are observed to be abnormal, replace the associated tube before making further tests. If the replacement tube does not provide the correct waveform, reinsert the original tube.

If there is no trouble present in an equipment or system, a waveform observed at a point in the equipment should closely resemble the reference waveform given for that test point. The reference waveforms supplied with maintenance literature are the criteria of proper equipment performance. However, test equipment characteristics or usage can cause distortion of the observed waveform, even though the equipment or system is operating normally. Several of the most common causes of these conditions are summarized as follows:

1. The leads of the test oscilloscope may not be placed in the same manner as those preparing the reference waveforms, or the lead lengths may differ considerably. This is particularly significant in the case of shielded test leads, where the capacitance per unit length is a factor.

2. A type of test oscilloscope having different values of input impedance, different sweep durations, or different frequency response may have been used.

3. The equipment operating (and servicing) controls may not have settings identical to those used when the reference waveforms were prepared. This condition is normally to be expected when servicing adjustments are made in terms of their effect on the shape and amplitude of an observed waveform.

4. The vertical or horizontal amplitudes of the reference and test patterns may not be proportional. This will produce apparent differences between the waveforms when actually there is no difference.

Whether or not a minor waveform discrepancy may be disregarded depends upon the type of circuit being traced. A minor discrepancy is not regarded as significant unless the nature of the discrepancy indicates faulty operation of the equipment. In general, time should not be wasted in searching for faults when relatively minor differences are detected between the reference waveforms and those obtained by test.

Modular Units

The demand for small, maintainable circuitry in military equipment has led to many different construction techniques. One of the most popular is modular construction. Since modular assemblies incorporate several subminiaturized features not found in conventional

equipment, some specialized knowledge and tools are required for efficient repair and maintenance.

A few definitions are helpful in understanding the terms involved. A module is defined as "a unit or standard of measurement; a fixed dimension." A modular assembly has outline dimensions which are multiples of a module. An equipment which consists of replaceable assemblies (any type) is said to be of unitized construction. Modular construction, then, is a type of unitized construction consisting predominantly of modular assemblies.

For example, think of a carton of cigarettes. If each pack were a modular assembly, the carton would be an equipment of modular construction. Notice that the packs can be arranged differently without changing the outside dimensions of the carton. Although the cigarette packs are all the same size, the assemblies in many equipments are not.

The original concept of many modular assemblies was that they should not be maintained in the field. The intention was to replace the assembly and ship it back to some repair facility. As assemblies became more complex, the point was soon reached where the extensive supply system required for the replacement was too costly. Many equipments built during this initial stage were potted with some special ingredient to discourage maintenance personnel from tampering with the insides of a "black box."

When the Navy reassessed this concept, realizing that the Fleet must maintain everything it could, most of the equipment manufacturers began to make components accessible. However, many electricians are still convinced that modular assemblies are impossible to repair. This conviction may stem from a lack of experience in working with the printed circuits and the other components in modular assemblies. While it is true that special tools and techniques are required, it is also true that satisfactory repairs can be made to any printed circuit by using just a little care and common sense. Actually, with a little experience, repairs can be made as easily as in conventional assemblies often more easily because of improved accessibility.

REPAIR OF DEFECTIVE COMPONENTS.— One of the time-consuming elements of troubleshooting is the identification of specific components. In conventionally wired equipment, components are not always easy to locate, even the circuitry in the chassis can become confusing since related components are often positioned in decentralized areas of the chassis.

In equipment which includes printed circuit boards, identification of circuitry and components may be relatively simple. This type of circuit construction allows uniform placement of components and complete sectionalization of related circuitry. Just a quick, once-over glance of such circuitry is often all that an electrician requires to formulate the overall layout of the chassis in his mind and quickly focus his attention on the area of particular concern.

Many of the commercial manufacturers have developed methods of quick identification. One of the most common ways is to impose a grid over a drawing of the board, and then furnish a table which lists the part location. Another technique is to number points of interest on the schematic, then provide a pictorial guide to locate the points on the board.

Circuit tracing of the printed wiring board may be simpler than that of conventional wiring, due to increased uniformity. If the wiring board is translucent, a 60-watt light bulb placed underneath the side being traced will facilitate circuit tracing. Test points can be located in this manner without viewing both sides of the board.

Resistance or continuity measurements of coils, resistors, and some capacitors can be made from the component side of the board. In some cases, a magnifying glass will help in locating very small breaks in the wiring. Voltage measurements can be made on either side of the board. However, a needlepoint probe is needed to penetrate the protective coating on the wiring. Hairline cracks can be located by making continuity checks.

A number of general precautions are necessary when working with modular assemblies. Supervisory personnel should take steps to insure that the electricians in their shop or maintenance crew know and understand the rules set forth in the following paragraphs:

1. Observe power supply polarities when measuring the resistance of the circuits of modular assemblies containing transistors, or other semiconductors. Such parts are polarity and voltage sensitive. Reversing the plate voltage polarity of a triode vacuum tube will keep the stage from operating, but generally will not injure the tube. However, reversing the voltage applied to a transistor, or other semiconductor will ruin it very quickly.

Since transistors and similar components require different power supply connections, the personnel who work with these parts must always be alert in connecting test equipment. Make sure that the correct polarity and range are observed. Recheck the work before turning on the power—the wrong polarity will destroy the part.

2. Avoid applying a-c power operated test equipment or soldering iron without first making certain that powerline leakage current is not excessive. Use of an isolation transformer is a good precaution to employ with all test equipment and soldering irons operated on a-c power, unless it has been determined that the equipment contains a transformer in its power supply or shows no current leakage. With all test equipment (whether transformer-operated or not), it is good practice to connect a common ground lead first from the ground of the circuit to be tested, and then to the test equipment ground.

3. Avoid application of too high a signal from test equipment. The safest procedure is to start with a low output signal setting, and then proceed to apply the required signal levels. Be sure that the signal applied is below the rating given for the circuit under test. Relatively high current transients can occur when test equipment is connected to a circuit where low-impedance paths exist.

4. Avoid moving loose connections, disconnecting parts, inserting or removing transistors or similar components, and changing modular units while the equipment power is on or while the circuit is under test. Moving a loose connection, or any of the actions mentioned, may cause an inductive kickback. This can be prevented by being sure that all parts in the circuit are secure before starting the test or turning on the equipment power. Be sure to remove all possible capacitance changes from parts and test equipment before applying them to a modular assembly. When changing modular assemblies, be sure the equipment power is off.

DRAWINGS AND SCHEMATICS

The senior AE will find a two fold use for his ability to properly interpret schematics and drawings. The need to interpret drawings and schematics will continue to be a part of accomplishing his maintenance tasks. In addition, the senior AE will be required to assist the less experienced men in interpreting schematics. Often when working with the less experienced men, the need for simplified versions of these schematics and drawings will arise.

INTERPRETATIONS

Instruction manuals used by the AE may contain diagrams of various types; among these are schematic diagrams, block diagrams, wiring diagrams, interconnecting cable diagrams, mechanical drawings, and combinations of some of these types. These diagrams are normally used to present a great deal of information in a small space or to clarify complex and detailed written explanations. The ability to correctly interpret these diagrams will, to some extent, determine the level of technical knowledge and understanding the senior AE can achieve.

Schematics

Electrical and electronic schematics will comprise a large portion of the diagrams the electrician uses. Symbols are the building blocks of the schematic. The AE should be familiar with the basic symbols from past experience. The increasing use of semiconductors has added new symbols, and future developments will undoubtedly add more. A study of new symbols and a review of the older standard symbols should be helpful to the AE. A list of standard symbols can be found in Military Standard Graphical Symbols for Electrical and Electronic Diagrams, MIL-STD-15-1.

Another basic consideration in schematic interpretation is recognizing specific type circuits. Here again it may be advisable for the AE to review the basic circuits using electron tubes, semiconductors, or the two in combination. The basic training manuals (Basic Electricity, NavPers 10086-B, and Basic Electronics, NavPers 10087-B) offer one source of review material for these circuits.

Drawings

Included in the drawings used by the AE are block diagrams, signal flow charts, wiring diagrams, and mechanical drawings. As with schematics, the electrician will be familiar with some of these drawings from past experience. The use of block diagrams and signal flow charts to present the overall picture of equipment function is widespread. Although

these do not contain the details so often needed in accomplishing maintenance tasks; they are of great value in fulfilling training responsibilities and in providing overall continuity when working with partial schematics.

Wiring diagrams, especially in some current aircraft and equipments, have become quite complex. With the emphasis now placed on integrated electronic systems, a review of wire and cable identification markings and symbols that show the interconnection of units should be useful to most electricians.

The use of mechanical drawings and the inclusion of mechanical functions on electronic diagrams is increasing. This is due, in part, to the increased use of computers and automatic devices (electronically controlled and mechanically operated).

The electrician must understand mechanical symbols and basic mechanical principles in order to correctly interpret these drawings. The basic training courses comprise a source of some useful information in this field.

MAKING SIMPLIFIED VERSIONS

Making simplified versions of drawings is not as new to the AE as some may think. Each time the instructor draws a circuit to explain a point about a large schematic, he is in fact making a simplified version of the schematic. The electrician may make simplified versions of drawings for various reasons: to explain a portion of the drawing while working with someone; in connection with the formal training program; or quite often as a means of better understanding a complicated drawing himself.

When making a simplified version of a drawing, use standard symbols, especially in drawings used for training.

There are many possible ways to simplify a drawing. The AE must determine why the diagram needs simplification; this reason may indicate how to go about making the simplified version.

Section IV of the Service Instruction Manual for each electronic equipment contains schematics of circuits or sections of the equipment. These are simplified versions of parts of overall schematics which have been redrawn in order to group components of a particular circuit or circuits to facilitate understanding. While simplification is usually thought of as reducing the whole into parts, there are cases where combining drawings makes them more easily understood. In working with inexperienced men, it may be necessary to redraw a circuit to more closely resemble the basic circuit of this type.

SPECIAL MAINTENANCE PROBLEMS

As the ceiling for aircraft on extended flights has been raised higher and higher, many new types of operating and maintenance problems have developed. Some of the various types of equipment involved are generators, voltage regulators, electric motors, and solenoids. Electric brushes on generators, inverters, electric motors, and other rotating electrical machinery wear away very rapidly at high altitude (around 40,000 feet). Special brushes have been developed that have longer life at high altitude. Thus, it is advisable to use the proper type brushes and to check them more frequently when high altitude flying is being performed.

While most switches will break a circuit safely at sea level, their contacts may burn and in some cases even melt at high altitude. It has been found that double-break contact switches somewhat alleviate this fault. Since electric and electronic systems use special design switches for high altitude operation, when making a replacement it is necessary to use the proper type.

Other items that often fail during high altitude flights are electrical plugs and receptacles. A voltage breakdown occurs between the pins and shell along the surface of the insulating material. The result is a burned plug. This happens because the breakdown voltage is less at high altitude. For example, the breakdown voltage for a 1/4-inch airgap is about 3.7 times greater at sea level than at 40,000 feet.

This condition may be overcome by sealing the connector with a potting compound. This reduces the probability of arc-over between pins or between pins and the shell of the electric connector since the dielectric characteristics of the connector are improved. This sealing compound also protects the connectors from corrosion or contamination by excluding metallic particles, moisture, and aircraft fluids. For information regarding the application of a sealing compound consult the current publication on this subject.

ENVIRONMENTAL CONSIDERATIONS

In recent years the effect of environmental conditions upon the operation of electronic and

electrical equipment has greatly increased the maintenance problems of the electrician. These peculiar conditions may be grouped under the major headings of altitude, temperature, and humidity. At the extremes of these conditions special maintenance and operating procedures are required. Equipments required to function at these extremes frequently fail due to the effect of decreased air density, radical temperature changes, and moisture.

Continuous damp, warm air causes condensation of atmospheric moisture within equipment unless units are hermetically sealed or the interiors are maintained at a temperature higher than surrounding atmospheric temperatures. Condensed moisture forms leakage paths and causes corrosion. These climatic conditions promote rapid fungus growth which in itself has a corrosive effect on materials such as wire, switch contacts, and other metal parts.

Adverse Climatic Conditions and Their Effects

Humidity is a term describing the amount of water vapor in the air. It is usually expressed as a percentage of the total amount of water the air can hold at a given temperature. Thus, 50 percent means the air contains one-half the total water it can hold, and 100 percent means it contains all it is capable of holding. Air can hold more water as its temperature increases. In tropical areas the humidity varies between 60 and 100 percent. This high humidity accounts for the condensation of moisture, or sweating on various parts of electrical and electronic equipments when they undergo temperature changes. Condensed moisture on insulating materials reduces their insulating qualities and results in arc-overs and shorts between terminals. The water vapor also penetrates into the body of insulation, is absorbed, and causes similar effects. High humidity also causes corrosion of metals. Other sources of moisture which cause deterioration include fog, salt spray, and rain.

In general, equipment may encounter extreme temperatures, ranging from minus 65°F to a maximum of 135°F, under various climatic conditions of high humidity, fog, rain, salt spray, salt air, cold, insects, fungi, and dust. High temperature and moisture vapor cause rapid corrosion. Fungus and bacterial growths produce acids and other products which speed corrosion, etching of surfaces, and oxidation. This interferes with the operation of moving parts, screws, etc., and causes dust between terminals, capacitor plates, and other parts, which produces noise, loss in sensitivity, and arc-overs.

Variations of temperature cause moisture to be breathed through any small cracks, pinholes, or vents in the equipment. As the temperature rises, the air inside a piece of equipment expands and it is expelled, in part, through the openings and vents. When the temperature falls, the air inside the equipment contracts and outside air is admitted through all openings and vents. The moisture which is breathed destroys the insulating qualities of dielectrics and corrodes metals.

Fungus is a form of plant life which feeds on materials of vegetable and animal origin including paper, cotton, etc., and such things as dead insects and other fungi. These may be spread by wind, dust, dirt, and insects, such as ants, flies, and mites. Growth may take place on materials other than those of organic origin if a spot of dust or other nutrient substance is present. Fungi thrive in the high humidities and temperatures. Fungus growth causes decay, accelerates the deterioration of insulating materials, and short circuits items such as relays, jacks, and keys. The inclusion of a fungicidal compound in the manufacture of the equipment retards the growth of these fungi.

Electronic and electrical package compartments cooled by ram air or compressor bleed air are subjected to the same conditions common to engine and accessory cooling vents and engine frontal areas. While the degree of exposure is less because of a lower volume of air passing through and special design features incorporated to prevent water formation in the enclosed spaces, this is still a trouble area that requires special attention. Circuit breakers, contact points, and switches are extremely sensitive to moisture and corrosive attack and should be inspected for these conditions as thoroughly as design permits during routine checks. If design features hinder examination of these items while in the installed condition, advantage should be taken of component removals for other reasons, with careful inspection for corrosion required before reinstallation. Treatment of corrosion in electrical and electronic components should be performed only by or under the direction of personnel familiar with the function of the unit involved,

as conventional corrosion treatment may be detrimental to some units.

Even though protective paint systems and extensive sealing and venting provisions are used in battery compartments, these compartments continue to be corrosion problem areas. Fumes from overheated battery electrolyte are difficult to contain and will spread to all adjacent internal cavities causing rapid, corrosive attack on unprotected surfaces. If the battery installation includes an external vent opening on the aircraft skin, these areas should also be included in the battery compartment inspection and maintenance procedure. Frequent cleaning and neutralization of acid deposits with sodium bicarbonate solution will minimize corrosion from this cause. This will continue to be a serious problem area until all battery installations are replaced with air-driven generators.

Climatic Deterioration Prevention

Most new equipment is given a climatic deterioration prevention treatment which provides a reasonable degree of protection against fungus growth, moisture, corrosion, salt spray, insects, cold, desert heat, etc. The treatment involves the use of a lacquer or varnish coating material applied with a spray gun or brush. Detailed instructions dealing with the treatment of corrosion problems may be found in Corrosion Control for Aircraft, NA 01-1A-509.

RADIO NOISE INTERFERENCE

Suppression of radio interference is a task of first importance to maintenance personnel. The problem has increased in proportion to the complexity of both the electric system and the electronic equipment. The aircraft, the engine, the electric system, and the electronic equipment are involved in the problem. Almost every component of the aircraft is a possible source of radio interference, which is the main factor in preventing the operation of receivers at full sensitivity. All personnel concerned should be familiar with the problem of radio noise and how to eliminate it.

The overall effect of radio interference of any kind is to impair or deteriorate the performance and reliability of radio and electronic sets or systems. The interference may act directly by actual deterioration of the equipment response, or indirectly by wearing down the patience and tolerance of the human operator. Either way, the result is the same, since combat efficiency is materially reduced.

The AE should know the following:

1. What radio interference is.
2. Where the interference originates.
3. How it gets into equipment.
4. How to identify it.
5. How to suppress it at its source.
6. How to segregate its path of entry into a receiver.
7. How to prevent its entry into a receiver.
8. What considerations enter into the design of an interference-free equipment.
9. How to position and install electrical and electronic devices.

This information is presented in detail in the publication, Reduction of Radio Interference in Aircraft, NavAir 16-1-521. Some of the most important of this information is presented briefly in the following pages.

Sources of Radio Noise

Sources of radio noise are divided into three general groups—atmospheric static, precipitation static, and manmade radio noise.

ATMOSPHERIC STATIC.—Atmospheric static, or "atmospherics," is a burst of RF energy caused by electrical discharges in the atmosphere. Although the frequency spectrum of atmospheric static is very wide, only frequencies in and below the high-frequency band propagate far enough to be very troublesome at long distances from the electrical disturbance. Therefore, UHF and VHF receivers are seldom troubled by atmospheric static. Reduction of such static is obtained by the use of frequency modulation, directional antennas, and noise-limited circuits. Frequency modulation is not used extensively in aircraft radio communication because of the bandwidth requirements.

PRECIPITATION STATIC.—Precipitation static is caused by the development of large static charges on the aircraft when it is flown through snow, rain, ice crystals, or dust clouds. An aircraft can build up a charge of several hundred thousand volts in a few seconds. The resulting high-voltage gradients at extremities and sharp points exceed the breakdown strength of air and cause noisy corona discharges. The conventional radio antenna, which must stand away from the body of the aircraft to be of effective height, is exposed to high electric fields. This means that corona discharges occur first in the antenna system, the very place that is

most sensitive to noise. Precipitation static is reduced by using a completely insulated antenna system—that is, by using highly insulated wire instead of bare wire, and by insulating all connections and supports for the antenna wire. Precipitation static is reduced also by eliminating all sharp metal projections from the aircraft and by installing dischargers, which quietly discharge accumulated static charges at a high rate. A discharger consists of silver-impregnated cotton wicking encased in a flexible plastic tube with an aluminum mounting lug. The many fine high-resistance fibers provide a multitude of discharge points. The resulting discharges are quiet up to very high currents. For detailed information on precipitation static refer to Installation and Maintenance Instructions Manual, Anti-Precipitation Static System, NA16-1-518.

The effect of precipitation static is a loud hissing or frying noise from the speaker or headset of the radio equipment and interference (grass) on the picture tube of visual output receivers. As an AE, you should not be too concerned with precipitation static since it is produced only when the aircraft is flying. Also, the preventive measures that are taken are the primary responsibility of other ratings. However, the AE should be aware of its characteristics because there is the probability that he may be asked to correct for radio interference that is caused by precipitation static. Unless the electrician knows its characteristics, he cannot determine for certain that the equipment for which he is responsible is not causing the trouble.

MANMADE RADIO NOISE.—The principal sources of manmade radio interference in aircraft are rotating electrical machinery, switching devices, pulsed electronic equipments, transmitter spurious emission, ignition systems, propeller control systems, receiver oscillators, nonlinear elements, a-c powerlines, and voltage regulators. The AE is not concerned with all these sources. Those with which he should be familiar are briefly discussed.

1. Rotating electric machines are a major source of radio interference. The types of interfering voltages generated by d-c machines are:

a. Switching transients as the brush moves from one commutator bar to another. This is usually called commutation interference.

b. Random transients caused by varying contact between brush and commutator. This is usually called sliding contact interference.

c. Audiofrequency hum (commutator ripple).

d. Radiofrequency and static charges built up on the shaft and rotor assembly.

Direct-current motors used in aircraft systems are of three general types—series wound, shunt wound, and permanent magnet field. The field windings of both series- and shunt-wound motors afford some "padding" or filter action against transient voltages generated by the brushes. The permanent-magnet motor's lack of such inherent filtering makes it a very common source of interference. It must be emphasized that the size of a d-c motor has little bearing upon its interference generating characteristics. The smallest motor aboard may well be the worst offender.

The output of an ideal a-c generator is a pure sine wave. A pure sine-wave voltage is incapable of producing interference except at its basic frequency. However, the ideal waveform is difficult to produce, especially in small machines. Practically all types of a-c power generators currently used in naval aircraft have been proven to be potential sources of interference at other than the output power frequencies. This interference may be produced by harmonics of the power frequency, caused by poor waveform; by commutation interference (series-wound motors); and by sliding contact interferences (alternators and series-wound motors). It should be noted that a-c motors that do not use brushes are almost never sources of interference.

2. Switching devices make abrupt changes in electric circuits. Such changes are accompanied by transients capable of interfering with the operation of radio and electronic systems. The simple occasionally operated manual switch is of little consequence as a source of interference. Examples of frequently operated switching devices capable of appreciable or serious interference are relays, vibrators, and thyratrons.

Since relays are used almost exclusively to control large amounts of power with relatively small amounts of power, they are always potential interference sources. This is especially true when they are used to control inductive circuits. Relay actuating circuits should not be overlooked as interference sources, because even though the actuating currents are small, the inductances of the actuating coils are usually

quite high. It is not unusual for the control circuit of a relay to produce more interference than the controlled circuit.

Induction vibrators are essentially double-pole double-throw relays which operate at a constant rate. As in any induction type switch or relay, there are two sources of switching transients, the inductive field contacts and the switching contacts. The output waveform of the vibrator is essentially rectangular at some audiofrequency. Its harmonic content is high and filtering is difficult.

Because of its interfering capabilities, the vibrator is seldom used as a radio power source in naval aircraft except for certain commercially available radio equipments found in small auxiliary aircraft. The principal use of inductive vibrators in naval aircraft is in connection with engine ignition systems.

Thyratrons are gas-filled, grid-controlled, electronic switching tubes which are used for many purposes. Among the most common uses are keyer tubes in radar modulators, rectifiers in regulated power supplies, rectifiers in servosystems, and relay applications. The current in a thyratron is either all ON or all OFF; there is no in-between. Since the time required to turn a thyratron ON is only a few microseconds or less, current waveforms in thyratron circuits are always steep fronted. As a result, they are rich in radio interference energy.

3. Ignition systems for internal combustion engines produce pulses of energy capable of interfering with radio reception at all frequencies in current use. The physical layout of the ignition's distribution system is such as to offer a very favorable radiation system. The lengths of wire between the distributor and the plugs become very effective antennas at wavelengths shorter than about ten times the length of the lead. Further, the radial arrangement of the wires assures polarization in all planes.

Unless effective preventive action is taken, ignition systems are highly potent sources of radio interference capable of complete destruction of radio reception within their effective fields. Fortunately, the problem of ignition interference is a very old one with a long history of development, effort, and improvement. Current aircraft engine ignition systems are completely enclosed in metallic shielding harnesses. These shielding harnesses are so effective (when properly maintained) that the ignition interference problem has been reduced to a secondary problem of proper maintenance.

4. Propeller systems, whether hydraulically or electrically operated, are potent generators of radio interference. This interference may be derived from propeller pitch control motors and solenoids, governors and associated relays, synchronizers and associated relays, deicing timers, and relays for power equipment.

Propeller control equipments generate clicks and transients as often as 10 times per second. The audiofrequency envelope of commutator interference varies from about 20 to 1,000 Hz. The propeller deicing timer generates intense impulses at a maximum rate of about 4 per minute.

Values of current in the propeller systems are relatively high. The generated interference voltages are therefore severe. They are capable of producing moderate interference at frequencies below 100 kHz and above about 1 megahertz, with severe interference at frequencies that lie between these extremes.

5. A nonlinear element may be defined as a conductor or semiconductor whose resistance or impedance varies with the voltage applied across it. Nonlinear elements that may cause radio interference in aircraft, in the order of their commonness, are overdriven vacuum tubes, oxidized or corroded joints, cold solder joints, and unsound welds. In the presence of strong signals, a nonlinear element behaves as a detector or mixer, producing harmonics and sum and difference frequencies from signals applied to it.

6. Alternating-current power sources produce radio interference of a broadband nature. In a-c powered equipments, a-c hum may appear at the power frequency or at the rectification ripple frequency. The rectification ripple frequency is twice the power frequency times the number of phases. Normally, aircraft systems utilize only single- and 3-phase sources at 400 Hz. Full-wave rectification single-phase 400-Hz power gives a ripple frequency of 800 Hz; a 3-1 phase source yields 2,400 Hz. This ripple can produce interference varying from annoyance to complete unreliability of equipment, depending on its severity and its coupling to susceptible elements.

7. Electromechanical and carbon-pile voltage regulators are used in naval aircraft.

The electromechanical regulator is common in older types of aircraft. It is essentially a fast acting relay which switches resistance in and out of the generator field coils to maintain a nearly constant output voltage. As an

interference source, it has all the characteristics of a vibrator except regularity. Most of its interference voltage is produced by arcing at the contact points.

The carbon-pile regulator controls the generator field resistance by magnetically varying the compression of a stack of carbon wafers. If properly adjusted, no arcing occurs and the only interference voltage generated is a result of thermal agitation within the carbon pile. It is seldom severe. This type of regulator is not a serious source of interference.

Manmade radio noise is caused by electrical transients which occur during the operation of electrical or electronic equipment. In brief, manmade radio noise is generated whenever an electrical circuit is opened or closed abruptly, such as by a relay, commutator, or other make-and-break devices. A similar condition exists when large amounts of current are periodically and abruptly started and stopped, as in radar circuits. An electric spark is a generator of electrical disturbances which appear to cover the entire radiofrequency spectrum.

Suppression of Manmade Radio Noise

Suppression of radio noise has advanced to the point where the proper application of available techniques insures that receiving equipment installed in the aircraft operates at optimum efficiency. The suppression or elimination of manmade radio noise is based on the premise that if manmade it can be man-corrected. Four types of suppression techniques are involved.

Isolation.—Isolation is the easiest and most practical method of radio noise suppression and revolves around the possibility of separating the source of radio noise from the input circuits of the receiving equipments affected. As every radio noise source can be considered a small transmitter, it is obvious that the radio noise source and leads carrying radio noise energy should be kept as far away from receiver antennas or lead-ins as possible. In many cases, the radio noise in a receiver may be entirely eliminated simply by moving the antenna lead-in wire just a few inches away from the source of radio noise. The value of sufficient separation between sources of radio noise and receiver input circuits is not apt to be overemphasized. The isolation method of radio noise suppression is very popular as it has the advantages of not requiring any additional material or adding any additional weight.

Bonding.—Bonding is a very necessary means of radio noise control. It provides grounding of all insulated conducting objects on the exterior of the aircraft. When conducting objects are not grounded, flight through precipitative weather conditions causes high-voltage charges to build up on those objects. Repeatedly, the voltage becomes high enough to spark over to an adjacent ground member or the object discharges to the surrounding air by corona conduction. Either mode of discharge causes considerable radio noise.

Other important functions of bonding are to protect the aircraft and personnel from lightning discharges by equalization of potentials produced which might cause arcs and sparks in the aircraft structure, to provide a homogeneous counterpoise for radio transmission and reception, to provide power current return paths, and to provide a short path for bypassing RF noise. All electronic equipments should be grounded to the aircraft structure. This may be accomplished by using short bond straps or by sheets of high conductivity (copper or aluminum) metal where it is impossible to use a short bond strap.

All bonding jumpers must be kept as short and direct as possible. When practicable, these jumpers are not to exceed 3 inches in length. The use of two or more standard length jumpers in series to make up the necessary length is not allowed without approval from the proper authority.

Shielding.—Shielding is one of the most effective methods of suppressing radio noise. The primary object in shielding is to electrically "bottle up" the radio frequency noise energy. In practical applications, this means that the radio noise energy must be kept flowing along the inner surface of the shield. The use of good shielding is particularly effective in situations where filters cannot be used and are not particularly effective when they are used. A good example of this is where radio noise energy radiates from a radio noise source and the radiated energy is picked up by the various circuits that eventually connect to the receiver input circuits. It is obvious that it would be impractical to filter a number of leads or units that are influenced by the radio noise energy; hence, the application of effective shielding at the noise source itself is advisable for it eliminates the radiated portion of the

radio noise energy by confining it within the shield at its source.

Filtering.—Radio interference as radiated or conducted from a source may be of a single frequency or may cover an extended band of frequencies. When bonding, shielding, or isolation of the source proves ineffective as a means of reducing radio interference, it becomes necessary to employ filters to accomplish this reduction. A filter is defined as "a selective network which transmits freely electric waves having frequencies within one or more frequency bands and which attenuates substantially electric waves having other frequencies." The size of a filter may vary widely, depending on the voltage and current requirements as well as the degree of attenuation desired. Filters are usually incorporated in equipment known to generate radio interference, but these filters are often inadequate, and in many cases it is necessary to add external filters to these equipments. This is especially true if the source of interference is coupling interference to paths of entry to a receiver other than the powerline.

The types of filters used in the reduction of radio interference vary with the application, but each of the general filter types may be found to be particularly adaptable to some specific situation. Most of the electrical devices connected to powerlines have features required for their operation, which are conducive to the generation of radio interference. The interference generated by these devices, unless properly attenuated, is impressed upon the powerlines and conducted to the receivers. It may also be conducted into the receivers by inductive coupling to other wiring associated with the receivers. This interference, unless attenuated by means of filters, is then transmitted along these powerlines, entering the receivers at the powerline input; or this interference may be radiated somewhere along the powerlines and enter the receiver by means of the antenna system.

Filters are of four kinds and are defined as follows:

Low-pass filter, which introduces negligible attenuation at all frequencies below a certain frequency, called the cutoff frequency, and relatively high attenuation at all higher frequencies.

High-pass filter, which introduces negligible attenuation at all frequencies above a certain frequency, called the cutoff frequency, and relatively high attenuation at all lower frequencies.

Bandpass filter, which introduces negligible attenuation at all frequencies within the range between two frequencies, and relatively high attenuation at all other frequencies.

Band-elimination filter, which introduces negligible attenuation at all frequencies outside a certain range, and relatively high attenuation at all frequencies inside that range. (NOTE: For information that covers the theory of operation of these filters refer to Basic Electronics, NavPers 10087-B.)

The normal characteristics of a filter are obtained only when the filter is properly terminated in its characteristic impedance.

A wave trap is a filter or network especially designed to reject certain frequencies, or bands of frequencies. Networks of this type may be installed at the antenna of the transmitter or receiver in order to attenuate frequencies outside of the assigned frequency range of the equipment. All such networks must have low insertion, loss, or attenuation, for the pass frequencies. In the design and construction of wave traps, the insertion loss is usually below 2 db.

There are two basic circuit configurations for filter networks, the pi-section and the T-section. Each may be broken down into half sections which have an inverted L-shape and are known as L-section filters. If a number of pi- or T-sections are connected in series to form a filter, the resultant network is called a ladder network. Any of the above circuit configurations may be used for radio interference elimination.

In general, the use of simple capacitor filters is to be preferred over that of the more complicated network filters in cases where this type of filter provides the required degree of radio interference attenuation. In this method, the radio noise energy passes through the capacitor to ground and then back to its source. This short-circuiting effect is due to the fact that the capacitor offers a very low impedance path across the noise source terminals.

A given capacitor is effective in bypassing only a limited range of radio interference frequencies because of its internal inductance and the inductance of the connecting leads. The inductance of the capacitor depends upon its capacity, the material of which it is fabricated, and the length of the connecting leads. The capacitor leads are the major contributors to the inductance of capacitors. For these reasons, small mica capacitors with short leads are

more effective as RF filters at high frequencies than large paper capacitors with normally long leads. Electrolytic capacitors should never be used as RF filters because of the danger of dielectric breakdown.

The popularity of the capacitor type filter is due to the fact that the current used for operation of the radio noise source does not have to pass through the filter. The only energy passing through the filter is the radio noise energy. The most important limiting factor in the choice of a capacitor type filter is the breakdown voltage rating of the capacitor. It must be well above the voltage used to operate the source of radio noise to be filtered. For example, where a 24-volt source of noise is to be bypassed with a capacitor, the working voltage of the capacitor should be at least 50 volts.

CHAPTER 4

ADVANCED ALTERNATING-CURRENT THEORY

The first part of this chapter deals with basic a-c functions, circuit characteristics, and definitions. These topics are fully explained in Basic Electricity, NavPers 10086-B; however, they are briefly reviewed in this chapter for purposes of continuity between Basic Electricity and AE 1 & C. Basic a-c theories and relations must be thoroughly understood before you can make effective progress in studying the more complex relations and mathematical processes.

The latter part of this chapter deals with the solution of a-c problems by use of complex quantities which are represented by rectangular and polar vectors. This is not discussed in other Rate Training Manuals that you are required to study. You should be able to use these forms of mathematics before beginning the study of polyphase systems. Rectangular and polar quantities will be used to analyze and explain polyphase systems and machinery.

VECTORS

VECTOR REPRESENTATION OF VOLTAGES

Mathematicians have developed a convenient means to enable the AE to add forces together easily and quickly. The name of this method is vector addition. Vectors are simply lines drawn to scale and in the proper direction to indicate the magnitude and direction of the forces which are to be added or subtracted. For example, suppose a vector 1 inch long represents a voltage of 10 volts. Then a 2-inch vector would represent 20 volts. Vectors are useful when analyzing alternating currents and their emf's. If a review of vectors is needed at this time, refer to Basic Electricity, NavPers 10086-B, chapters 12 and 13.

Inductive Impedance

An inductive impedance may be a single coil, or a complex network whose overall characteristics are inductive in nature. All such impedances, however, have at least one characteristic in common — they will not permit their currents to change rapidly enough to coincide with changes in the impressed voltage. As a result, the current wave through an inductive impedance never quite catches up with the wave of impressed voltage. This is commonly referred to as a current "lag"; and in a theoretically pure inductance, with no resistive loss whatsoever, this lag would amount to a full 90°. In practice, however, there is also some opposition to current flow which is resistive in nature. In a purely resistive impedance, there will be no angular difference between the current wave across the resistor and the wave of impressed voltage. Thus, in a theoretically pure resistance, the angular difference between current and voltage waves across the resistor would amount to 0°. From the foregoing, you can see that an impedance comprised of elements which are both resistive and inductive would cause a circuit current lag of an amount between 0° and 90°. The amount of lag would depend on the ratio of inductive reactance to resistance at a given frequency.

PHASE ANGLE AND POWER FACTOR.— The angular difference (phase angle) between circuit current and impressed voltage has a direct bearing on the amount of power (watts) actually dissipated in a partially inductive impedance. Resistive opposition to current flow constitutes an actual power loss, because energy is dissipated in the form of heat. Inductive opposition to current flow does not cause a power loss, because energy is transferred alternately to and from the magnetic field formed around the inductor.

The energy stored in this field during one-half of an alternating cycle is returned to the source by the inductor during the other half of the same cycle, so that the average loss equals zero. Thus, the amount of actual power loss (true power) in a partially inductive impedance depends on the ratio of resistance to inductive reactance. The true power in a circuit also depends on how the various elements are connected in relation to each other. The effects of changing connections are discussed later. Figure 4-1 is used to show how power loss is affected by the ratio of resistance to inductive reactance.

Both (A) and (B) in figure 4-1 represent simple impedances with inductive characteristics. In both cases, applied voltage is the same (10 volts). Also, total circuit impedance (5 Ω) and line current (2 amp) are the same. If an ordinary a-c voltmeter were connected across points A and B and an ammeter between points C and B, identical readings of voltage and amperage would be obtained from both circuits. At a glance, it might seem that both circuits are consuming identical amounts of power. This is not true. The vector diagrams represent the average relative magnitude of resistive and inductive voltage drops. More important, they also show the differing phase angles of the two circuits. This difference is significant.

Coils E_C and I_C are arranged so that if the voltage wave through E_C is completely in phase with the current wave through I_C, maximum meter torque will result. The indicator would point to 0°. Conversely, if the voltage and current waves were a full 90° out of conjunction (phase), meter torque would be minimum and the indicator would point to 90°. Since the true power in an a-c circuit is directly indicated by the phase angle, this "phase angle indicator" may be calibrated in watts.

Vector diagrams may be used to determine phase angle. Once the angle is known, its

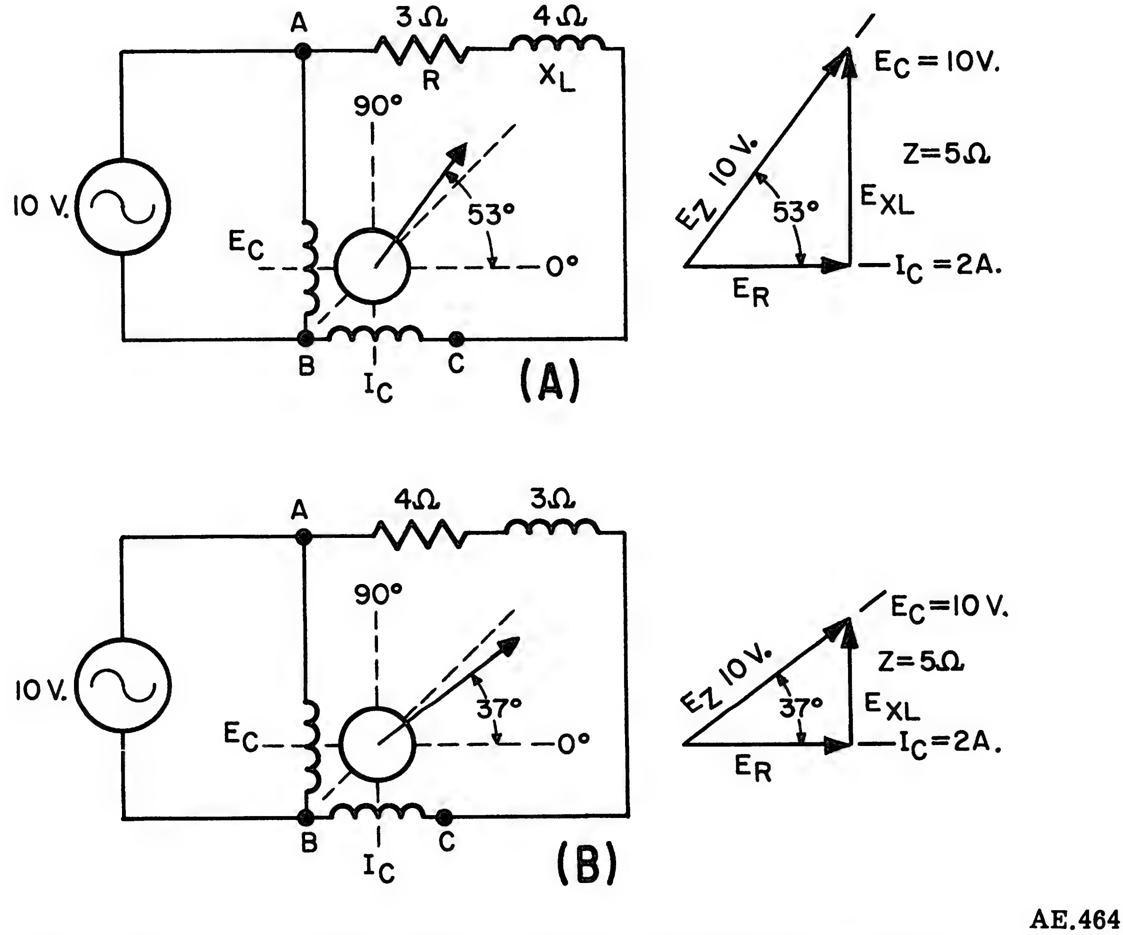


Figure 4-1.—Vector representation of voltages in an inductive impedance.

numerical cosine (cosine of the phase angle) may be multiplied by 100 to yield a percentage figure, or power factor. This figure indicates directly what percentage of apparent power is dissipated in heat, and thus indirectly what percentage is merely a circulating interchange of energy between the voltage source and the circuit inductance.

The cosine of the phase angle may also be multiplied by line voltage and current to obtain true power in watts. This would be done where the actual number of watts must be known, rather than the percentage of true power to apparent power. Vectors serve well in analyzing simple circuits, but would be clumsy if used in more complex problems. However, complex processes are based on the fundamental a-c relations usually represented by vectors. Before commencing the study of rectangular and polar notation, you must be thoroughly familiar with these basic relations.

Capacitive Impedance

A capacitive impedance may be a single capacitor or a complex network whose overall characteristics are capacitive in nature. A characteristic common to all capacitive impedances is that they will not permit their voltages (capacitor charge) to change rapidly enough to coincide with changes in the impressed current. As a result, the current wave through a capacitive impedance is always ahead of the wave of voltage across the same impedance. This is commonly referred to as a current "lead."

In a theoretically pure capacitance, with no resistive loss whatsoever, this lead would amount to a full 90°. In practice, however, there is always some opposition to current flow, which is resistive in nature. The current could never attain a full 90° lead, though some high quality capacitors approach it very closely. Consequently, the phase angle of a capacitive impedance will depend on the ratio of capacitive reactance to resistance.

PHASE ANGLE AND POWER FACTOR. — The angular difference (phase angle) between circuit current and voltage has a direct bearing on the amount of power actually dissipated in a partially capacitive impedance. The phase angle, and thus true power, is again determined by the ratio of reactance to resistance; in this case the reactance being capacitive in nature.

Refer again to figure 4-1. If the inductors in both circuits were replaced by capacitors of the same ohmic reactive values (4 Ω and 3 Ω), the phase angle in both cases would remain the same. The magnitude of line current and true power in each circuit would also be unchanged. There would be, however, one significant difference — rather than current (I_C) lagging voltage (E_C), the relation would be reversed. Current would lead voltage, but still by the angles indicated.

The apparent opposition to current flow evidenced by the capacitor (capacitive reactance) does not constitute an actual power loss. As with the inductance, there is a reciprocating interchange of energy between the capacitance and source of impressed voltage, with a net energy (power) loss of zero. Energy is alternately stored and released by the capacitor's electrostatic field (charge) rather than by a magnetic field such as that in an inductor.

Inductive and Capacitive Impedance

An impedance may have individual elements or branches which, in themselves, may be inductive or capacitive in nature. In such a case, however, the overall characteristic of the impedance is determined by the larger reactance.

Figure 4-2 (A) represents an impedance composed of both inductive and capacitive elements, as well as resistance. The voltage from points A to B is always 180° out of phase with the voltage from points B to C, assuming both reactances are pure. Consequently, one may be subtracted algebraically from the other, as shown in the accompanying vector diagram. The resultant net reactive voltage, identified as $E_{XL} - E_{XC}$ in part (A) and as $E_{XC} - E_{XL}$ in part (B), determines the overall characteristic of the circuit; that is, part (A) is inductive in nature, while part (B) is capacitive. The true power is the same in either circuit. True power is determined by the phase angle. It does not matter whether current is leading or lagging. The wattmeter is deflected the same amount and in the same direction in either case, and cannot differentiate between an inductive or capacitive load.

VECTOR REPRESENTATION OF CURRENTS

In representing voltage vectors, series impedances were used, and circuit (line) current was used as a reference. This was done because only one current flows through the entire series

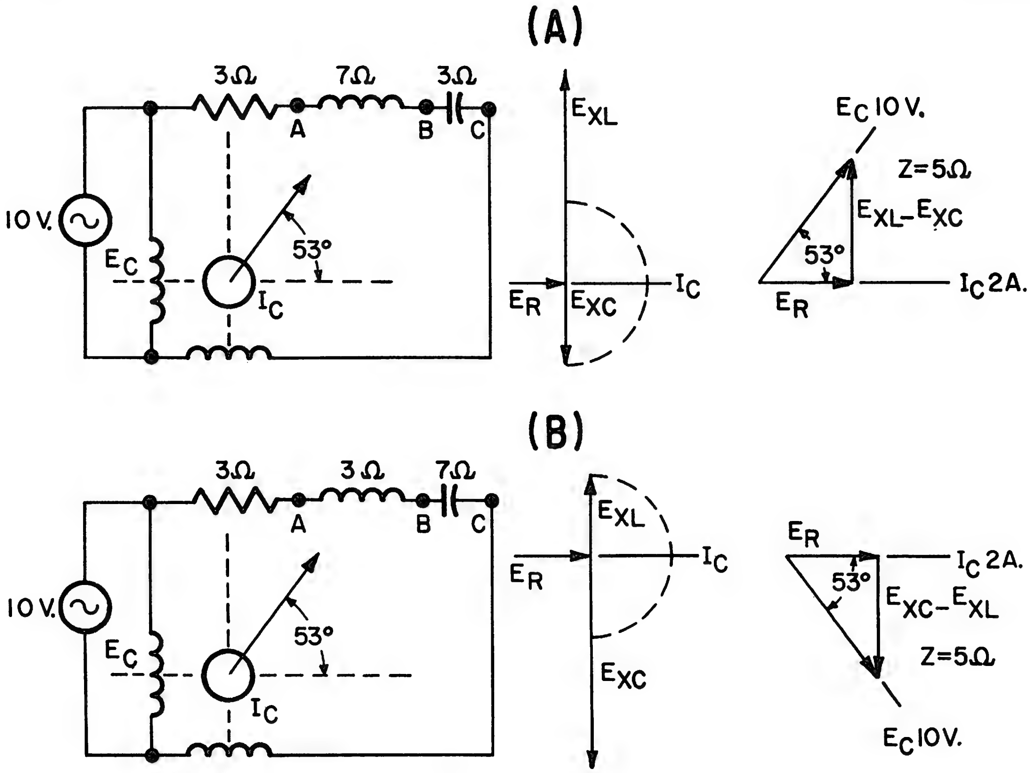


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Figure 4-2.—Vector representation of voltages in an inductive and capacitive impedance.

circuit. Thus, the various element voltages could be shown in relation to a common reference (current), and consequently in relation to each other. When solving or representing more than one current, however, it must be assumed that a parallel circuit is under consideration. Only in a parallel circuit may there be more than one current simultaneously.

Parallel branches connected to a common source have the same voltage applied across their terminals. For this reason, line voltage is used as a reference for laying out branch currents to show their relation to a common reference and to each other. In series, conflicting element voltages are resolved with impressed voltage to produce a common line current. In parallel impedances, conflicting element currents resolve into a single line current, and in some cases circulating currents, but all elements have a common terminal voltage.

In figure 4-3, the magnitude of each branch current may be obtained by simply dividing the line voltage by branch resistance, or reactance. Capacitive current is shown leading line voltage because it is characteristic for the current in any capacitive reactance to lead the voltage across its terminals.

The inductive current lags because of its inductive nature. The current vectors shown in (B) represent individual branch currents. I_{XC} and I_{XL} are 180° out of phase, and so may be subtracted algebraically to obtain the reactive current value represented by $I_{XL} - I_{XC}$ in (C). Their algebraic difference constitutes the actual value of current flowing from points A to B through X_C and X_L in part (A); that is, the reactive component of I_L is contributed to the circuit through points A and B, but the circulating interchange of current between X_C and X_L may be smaller, equal to, or larger than the reactive current component on the line. As can be seen, the overall circuit characteristic will be determined by which reactive branch current is the larger.

The impedance of figure 4-3 has an overall inductive characteristic. No power is used in the theoretically pure capacitive and inductive branches. Energy is dissipated across the resistor only, which is connected directly to the voltage source, and is thus relatively free

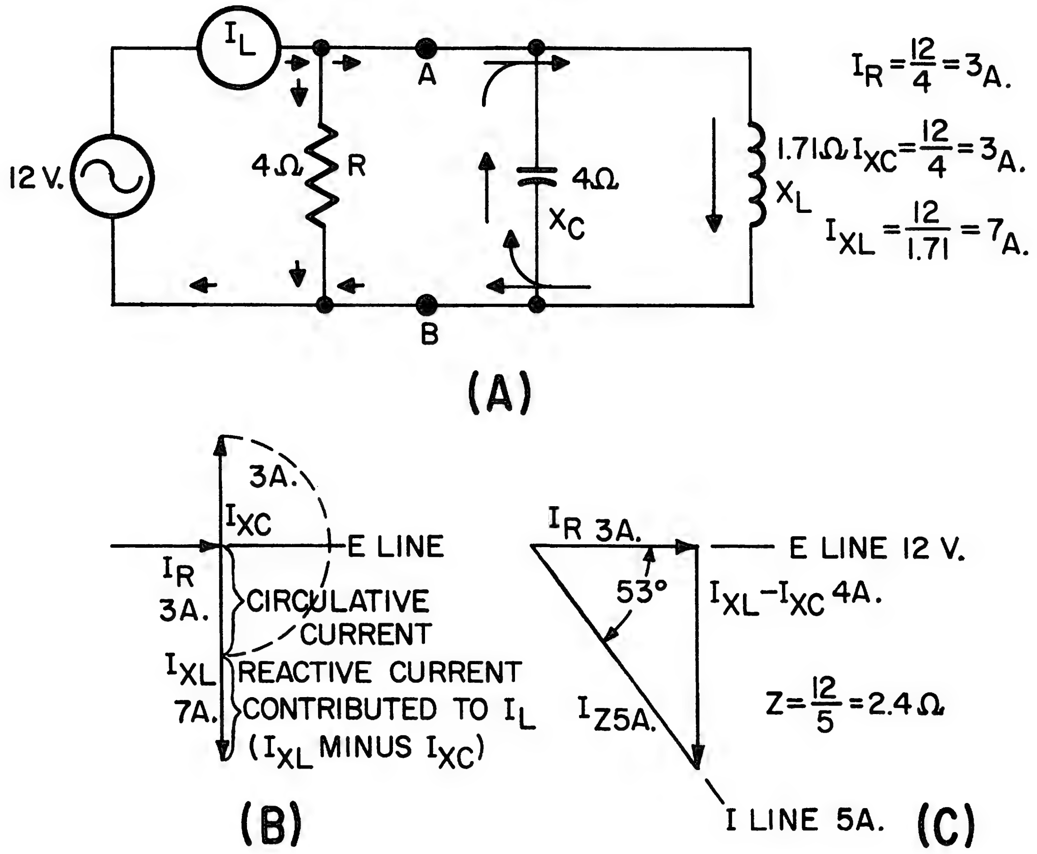

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Figure 4-3. — Relation of capacitive to inductive current.

from reactive influences. The reactive branches may be varied at will without changing the true power of the circuit as a whole. Assuming line voltage is fixed, energy current I_R would remain fixed; line current I_L would vary with changes in either X_C or X_L. If reactive current I_{XL} - I_{XC} ((C) of fig. 4-3) became greater, then line current I_L (I_Z in (C)) would also become somewhat greater. However, the compensating factor, as far as true power values are concerned, is the fact that angle θ would also increase. As this angle θ increases, the cosine of the phase angle decreases. In the formula for determining true power — volts x amperes x cosine of phase angle ($E \times I \times \cos\theta = P$) — note that if line amperage (A) increases, and the cosine of circuit phase angle ($\cos\theta$) decreases a proportional amount, true power (P) remains the same.

Energy and Reactive Currents

In practical circuits, there will be no purely reactive loads or branches. That is, some true power will be consumed by any load placed on a power source, such as an a-c generator or inverter. In addition, there will usually be a reactive, or VARS, load. Since the generator or inverter is supplying maximum power to its load when current and voltage are in phase, it is important that the power factor be kept as high as possible.

The load rating of an a-c machine is determined primarily by the internal heat it can withstand for long periods of time. Since current through its windings is the major cause of heating, a-c generators and inverters are rated in volt-amperes rather than in watts. A given magnitude of line current will cause a specific amount of heat, regardless of whether it is "energy" current or "reactive" current.

A current which is out of phase with its voltage is said to be composed of two components — energy current and reactive current. If a generator is supplying a highly reactive

load, it may be operating at its maximum allowable line amperage, and still not be delivering the proper amount of true power. More useful loads could not be added under these circumstances without exceeding the load rating of the generator.

Figure 4-4 represents an a-c generator supplying a partially reactive load. Each load branch has a different current characteristic than the other branches. Assuming the generator shown is rated at 5,000 VA, then it is supplying its full rated load. Figure 4-5 is a more complete representation of the same circuit.

Part (A) of figure 4-5 represents the progressive combining of separate branch currents, shown in sine waveform, into a single final line current wave, (I_{line}). Part (B) represents the same currents shown in vector form. Note that each reactive branch current is composed of both energy current (I_{RXC} and I_{RXL}) and reactive current (I_{XC} and I_{XL}). The subtriangle formed by I_{RXC} + I_{RXL} on one side and I_{XL} - I_{XC} on another represents the phase relations of the reactive branches only. The true power in the reactive branches equals I_{RXC} (17.35) + I_{RXL} (22.8) x 100v. (17.35 + 22.8 x 100 = 4,015 watts.) VARS in the reactive branches equals I_{XL} (27.15) - I_{XC}(10) x 100v. (27.15 - 10 x 100 = 1,715 VARS.) True power for the whole circuit is obtained when I_R is added to the complete triangle (4,700 watts). VARS remains the same, because the current through the resistive branch contains no reactive components.

The total a-c load, as far as the generator is concerned, could be reduced to the equivalent impedances shown in part (C). If power factor correction is to be made for a particular a-c generator or inverter, it is best to

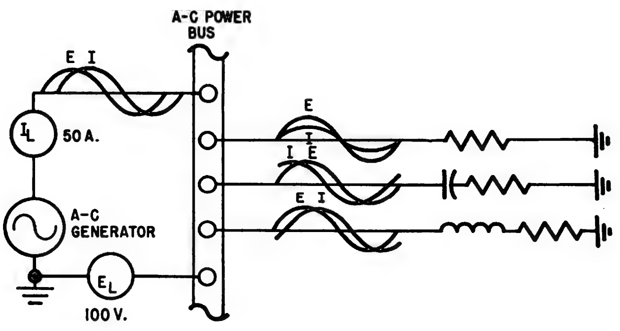

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Figure 4-4.—A-c generator supplying a multibranch load.

reduce the machine's load to a single simplified impedance in order to determine the nature and magnitude of correction to be made.

Assume that an additional resistive load must be connected to the a-c generator considered in figure 4-5. None of its existing loads may be disconnected. Since the generator is already operating at maximum rated current, this might seem impossible. Refer to figure 4-6 in connection with the following explanation. Part (A) represents the simplified load impedance before correction is made.

The generator is delivering 4,700 watts of power, and its line current is 50 amp. Obviously, no additional load can be connected without overloading the generator. In part (B), capacitive correction is connected; this causes the reactive component of line current to be reduced to zero. Circulating current at this point is increased, between the reactive elements of the generator's load, but line current through the generator is decreased from 50 amp to 47 amp. An additional useful load up to 3 amp may then be connected as shown in part (C).

RECTANGULAR NOTATION OF A-C QUANTITIES

DEFINITION OF RECTANGULAR VECTORS

Up to this point, vectors have been described as shown in figure 4-7 (A). That is, they have been visualized essentially as the hypotenuse of a right triangle. When described in this manner, a vector's magnitude, or length, from point 0 to A is given. In addition, its direction is also given as the number of degrees that the vector is laying away from a horizontal reference line. The number of degrees is symbolized by theta (θ). This is the polar vector form.

When the polar form is used, a vector is described in terms of its magnitude and direction. For instance, a vector 10 inches long laying at 30° above the horizontal line would be described as $10\underline{/30°}$. ($\angle$symbolizes "at an angle of"). If the magnitude of vector 0A in figure 4-7 (A) is known and θ is also known, the length of sides R and J could be determined, if required, by the use of trigonometry.

Vector 0A could also be accurately described in another manner, if only the length and direction of sides R and J are known. This method

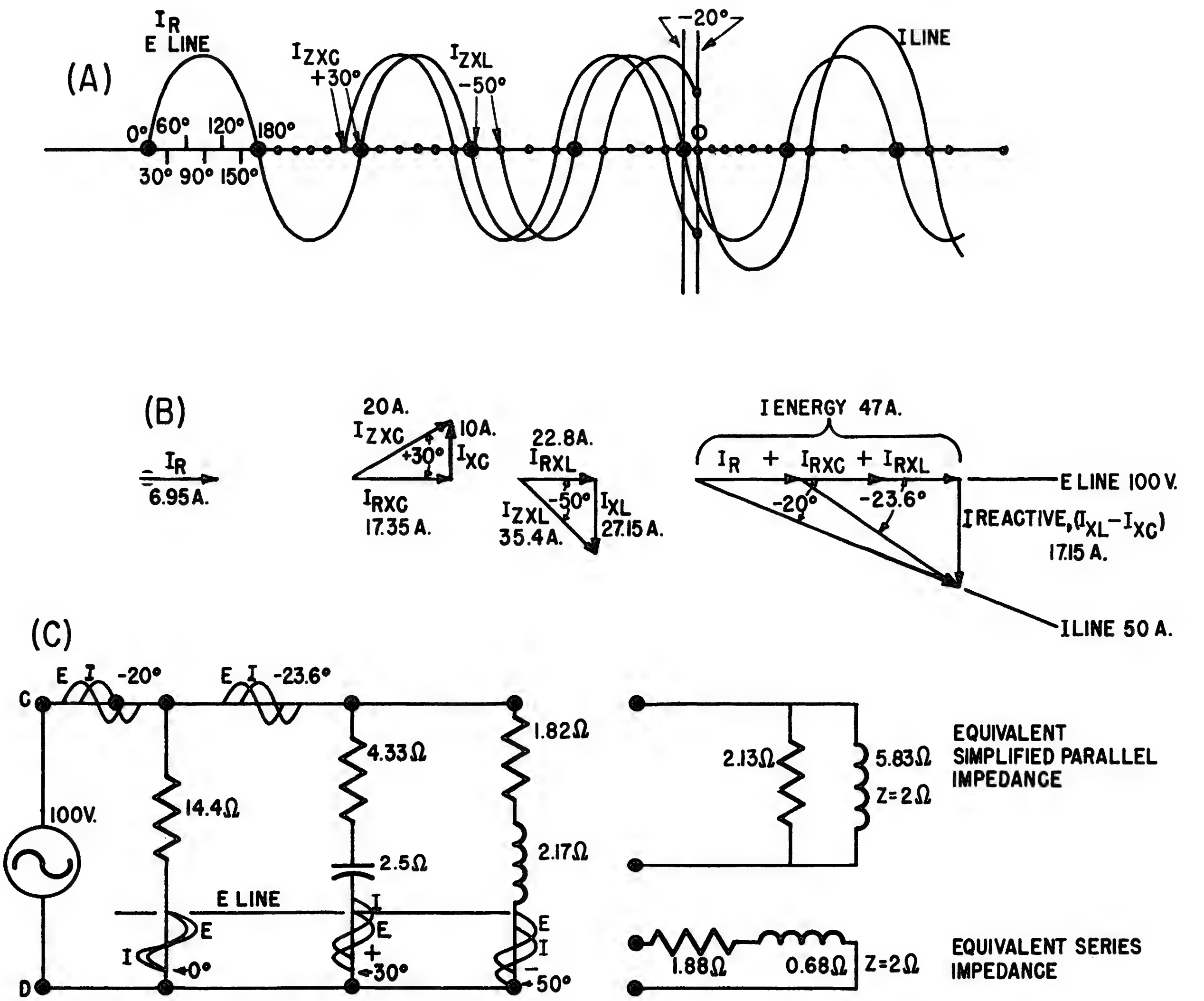

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Figure 4-5. — Representation of multibranch currents.

is illustrated in figure 4-7 (B). In this case, neither the actual length of vector 0A nor θ is known. Nevertheless, vector 0A may still be accurately referred to as vector R8.66 ⊕ J5, because R8.66 and J5 form a triangle of which vector 0A is the hypotenuse. (The symbol ⊕ means added vectorially.) Later, you will process vector quantities mathematically, using a similar form, without necessarily ever knowing the actual magnitudes and directions of the vectors on which you are working. They will simply be written in terms of their components, or sides. If vectors R and J are considered as two sides of a rectangle as shown in figure 4-7 (B), then vector 0A is the diagonal length of that rectangle; hence the term rectangular vector.

Since rectangular notation must be able to indicate direction as well as magnitude, then vector R must be able to lay either to the right or left of point 0, as shown in figure 4-7 (C). Also, vector J must be able to lay either above or below point 0. When vector R is to the right, it is given a positive (+) sign, or a negative (-) sign when laying to the left. Vector J is given a positive (+) sign when above the line, or a negative (-) sign when below. In this way, the distance and direction of a point anywhere within a circle, in relation to the middle of the circle, may be indicated by the signs and lengths of vectors R and J. This is given further illustration in figure 4-8.

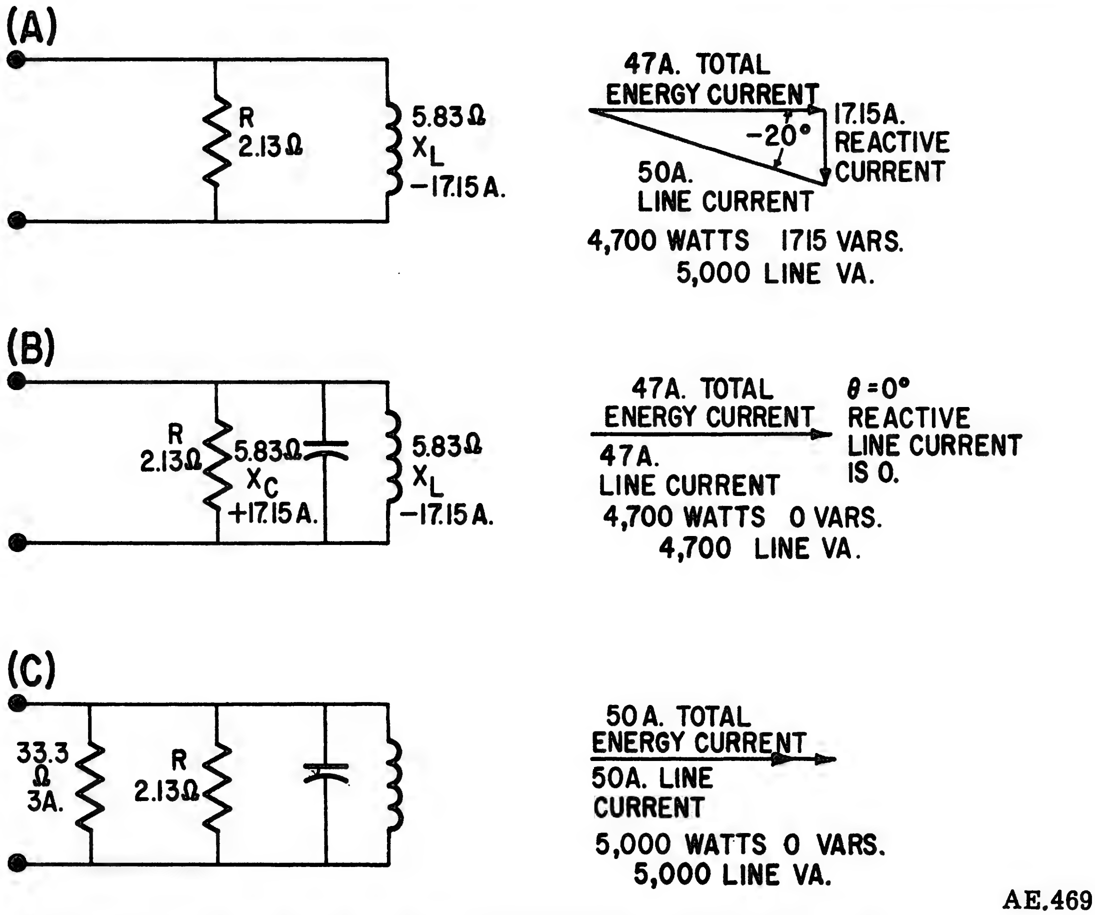

Figure 4-6. — Simplified impedances for balancing reactive loads.

In part (A), vector 0A is referred to as vector R3 - J4. In part (B) vector 0A is referred to as vector - R4 - J2. In part (C), vector 0A is 0 + J3; and in (D), it is -R3 + J0. Note that when a vector is perfectly vertical or horizontal, its rectangular description still contains two components, but one is included only as a zero value. In practice, the horizontal, or R, component is always stated first, and the vertical, or J, component is stated second. Also, the R is dropped, but its algebraic sign is kept; however, the J is never dropped. Therefore, vector 0A in figure 4-8 (A), for instance would be referred to more simply as 3 - J4, and that in (B) would be referred to as -4 - J2.

USE OF RECTANGULAR VECTORS

Rectangular vectors are commonly used to describe and identify a-c quantities in terms of their components. These quantities include impedance, admittance, current, voltage, and power. When expressing an impedance in rectangular form, the resistive component is always the first member, and the reactive component is the second, or J member. Also, rectangular representation of impedance always refers to components connected in series. There is no such thing as an impedance vector for parallel components. Total parallel impedance is solved only by dividing total current into line voltage. Figure 4-9 shows the various types of series impedances, and to the right of each appears the three common methods of representing each.

Referring to figure 4-9, note that impedances which are inductive in nature are different from those which are capacitive in the following significant way — the operator J is positive (+J) for inductive impedances and is negative (-J) for capacitive impedances. This is quite logical and easily remembered if you consider the voltage drops as they would occur across these impedances if they were connected in a circuit. That is, voltage leads (+J) across an

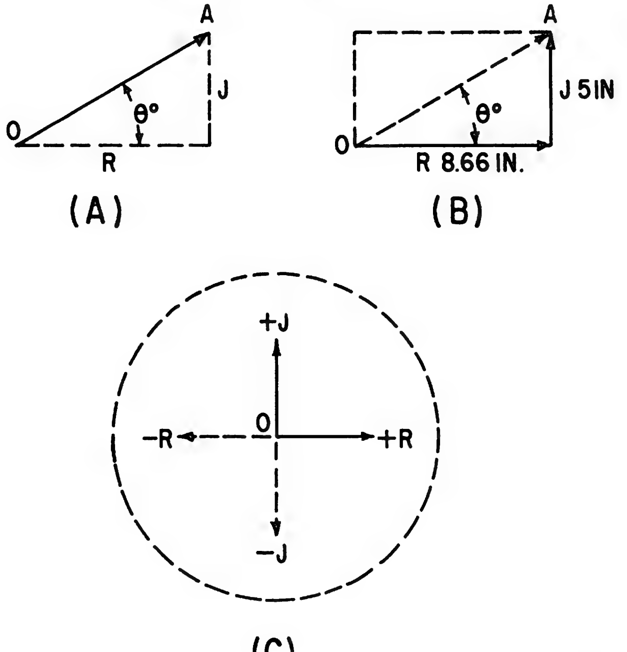

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Figure 4-7.—(A) Polar vector; (B) rectangular vector; (C) directional axes for rectangular vectors.

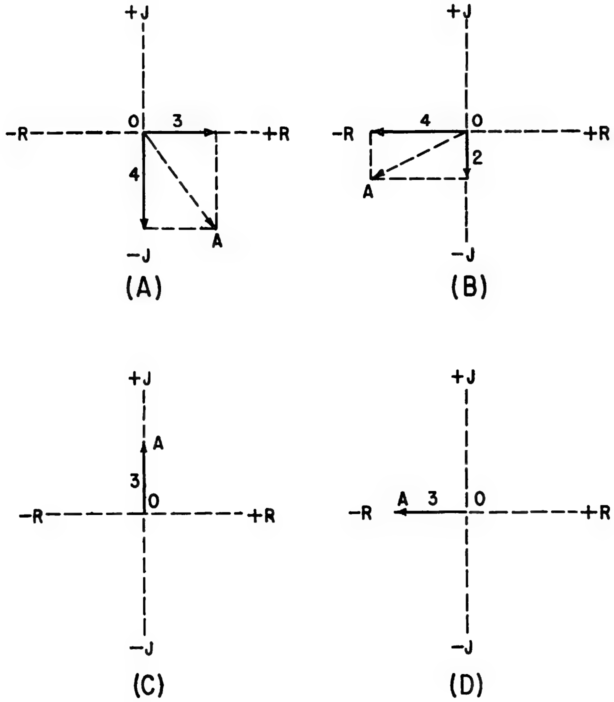

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Figure 4-8.—Representation of rectangular vectors.

IMPEDANCE	VECTOR FORM	RECTANGULAR FORM	POLAR FORM
$R=5\Omega$	$R=5\Omega$	$Z=5+J0\Omega$	$Z=5\angle 0°\ \Omega$
$X_C=7\Omega$	$X_C=7\Omega$	$Z=0-J7\Omega$	$Z=7\angle -90°\Omega$
$X_L=6\Omega$	$X_L=6\Omega$	$Z=0+J6\Omega$	$Z=6\angle +90°\Omega$
$R=6\Omega$ $X=8\Omega$	X_L Z R	$Z=6+J8\Omega$	$Z=10\angle +53.1°\Omega$
$R=8\Omega$ $XC=6\Omega$	X_C R Z	$Z=8-J6\Omega$	$Z=10\angle -36.9°\Omega$
$R=2\Omega$ $X_C=7\Omega$ $R=2\Omega$ $X_L=4\Omega$	R+R Z X_C-X_L	$Z=4-J3\Omega$	$Z=5\angle -36.9°\Omega$

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Figure 4-9.—Common methods of representing impedance.

inductance, and lags (-J) across a capacitance. Therefore, the algebraic sign of the J operator is the same for both voltage and impedance when these values are represented for a given circuit.

The algebraic sign itself is determined by the reactive nature of the circuit. This may be seen clearly by comparing the algebraic signs of the J operators as they appear in the impedance and voltage columns of figure 4-10. In summary, a plus (+J) is used for an inductive impedance or inductive voltage drop, and a minus (-J) is used for a capacitive impedance or capacitive voltage drop. Also, resistive voltage components are written first, while reactive voltages are always written second and preceded by ±J, as the case requires.

Refer again to figure 4-10. Notice that current and power notations for each circuit have their J operators preceded by algebraic signs which are opposite to those which refer to impedance and voltage (except in the top row, where the J factor is 0, and the algebraic sign is thus unimportant). Again, there is a logical reason for this, because the current through an inductance has a lagging (-J) characteristic, while current through a capacitance is leading (+J). The nature of a current may thus be indicated by the algebraic sign of its J factor. This would also provide a direct indication of

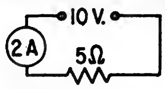
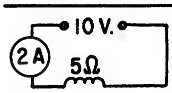
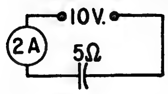
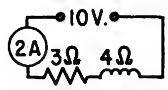
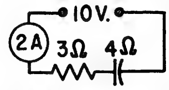
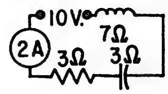
CIRCUIT	IMPEDANCE	VOLTAGE	CURRENT	POWER
	Z=5Ω OR Z=5+J0Ω	E_L=10 V. OR E_L=10+J0V.	I_L=2A. OR I_L=2+J0A.	AP=20 WATTS OR AP=20+J0W.
	Z=5Ω OR Z=0+J5Ω	E_L=10V. OR E_L=0+J10V.	I_L=2A. OR I_L=0−J2A.	AP=20 WATTS OR AP=0−J20W.
	Z=5Ω OR Z=0−J5Ω	E_L=10 V. OR E_L=0−J10V.	I_L=2A. OR I_L=0+J2A.	AP=20 WATTS OR AP=0+J20W.
	Z=5Ω OR Z=3+J4Ω	E_L=10V. OR E_L=6+J8V.	I_L=2A. OR I_L=1.2−J1.6A.	AP=20 WATTS OR AP=12−J16W.
	Z=5Ω OR Z=3−J4Ω	E_L=10V. OR E_L=6−J8V.	I_L=2A. OR I_L=1.2+J1.6A.	AP=20WATTS OR AP=12+J16W.
	Z=5Ω OR Z=3+J4Ω	E_L=10V. OR E_L=6+J8V.	I_L=2A. OR I_L=1.2−J1.6A.	AP=20WATTS OR AP=12−J16W.

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Figure 4-10. — Rectangular notation of a-c quantities.

the nature of the impedance through which the current is flowing (inductive or capacitive). When a current is represented in rectangular form, the first member indicates the energy (watt) component, while the J member indicates the reactive (VARS) component. This is one of the many convenient features of rectangular notation. That is, a direct indication of the true power to apparent power ratio is shown simply by describing the current in terms of its rectangular components. The close resemblance of a current vector to a power vector becomes apparent if you notice that both have identical algebraic signs preceding the J operator. The triangles inferred by both vectors will have the same shape and phase angle θ, though their actual magnitudes may differ.

When circuit power is expressed in rectangular form, the first member represents true power in watts, and the J member represents reactive volt-amperes (VARS).

The discussion up to this point has involved only the identification of a-c quantities in rectangular form. Some fundamental advantages have also been discussed. However, no mention has been made of the most important single advantage gained by the use of rectangular vectors, which is as follows: A-c quantities represented as rectangular vectors may be processed mathematically without direct use of trigonometric functions. The multiplication, division, addition, and subtraction of a-c quantities can be carried out by treating these quantities as simple binomials.

Addition

Addition of rectangular vectors is accomplished in the following manner:

Example:

Add 4 + J6 to -6 + J7

Solution:

$$\begin{array}{r} 4 + J6 \\ \underline{-6 + J7} \\ -2 + J13 \end{array} \text{ (answer)}$$

Subtraction

Subtraction of rectangular vectors is accomplished as follows:

Example:

Subtract 6 - J9 from -2 - J7

Solution:

Change the signs of the subtrahend 6 - J9 to -6 + J9, then —

$$\begin{array}{r} -2 - J7 \\ \underline{-6 + J9} \\ -8 + J2 \end{array} \text{ (answer)}$$

Multiplication

In multiplying rectangular vectors, the rules applying to multiplication of simple binomials still apply. This is done in the following manner:

Example:

Multiply 7 - J6 by 4 + J8

Solution:

(1)
$$\begin{array}{r} 7 - J6 \\ \underline{4 + J8} \\ 28 - J24 \qquad\quad \\ \underline{+ J56 - J^2 48} \\ 28 + J32 - J^2 48 \end{array}$$

(2) 28 + J32 + 48

(3) 76 + J32 (answer)

When a member of the product is preceded by a J^2, such as in the last line of step (1) in the foregoing problem, the J^2 is dropped and its sign reversed, as shown in step (2). The member is then combined to obtain the final answer, as shown in step (3). (A simple explanation of this requires a review of the J factors as follows: $J = \sqrt{-1}$, $J^2 = -1$, $J^3 = -J$, $J^4 = +1$. The AE should review complex numbers in Mathematics, Vol. 1, NavPers 10069-C, if further information is needed.)

Division

The division of rectangular vectors is the most complex of the four mathematical operations.

Example:
Divide 50 + J35 by 8 + J5

The first step is to convert the divisor 8 + J5 into a single number unaffected by the operator J. This is done by multiplying the divisor by its conjugate, 8 - J5. (The conjugate of any rectangular vector is that vector with the sign of its J operator reversed.) Multiplying any rectangular vector by its conjugate will produce a single number. For instance, 8 + J5 x 8 - J5 = 64- $J^2$25, or 89. Any fraction may have its numerator and denominator multiplied by the same number or quantity without affecting the value of the fraction. For instance, 3/8 x 4/4 = 12/32 = 3/8. Therefore, both numerator and denominator of the original example problem 50 + J35 ÷ 8 + J5 may be multiplied by the conjugate of the divisor without changing its value, as follows:

$$\frac{50 + J35}{8 + J5} \times \frac{8 - J5}{8 - J5} = \frac{400 + J30 - J^2 175}{64 - J^2 25}$$

This operation, after terms are collected, results in the original 50 + J35 ÷ 8 + J5 having been changed to the new form 575 + J30 ÷ 89. When each member of the numerator is divided by 89, the result is:

6.46 + J0.337 (answer)

POLAR NOTATION OF A-C QUANTITIES

DEFINITION OF POLAR VECTORS

A polar vector may be any ordinary vector. It is different from an identical rectangular vector only in the manner in which it is described. A vector in polar form is given in terms of its length, or magnitude, and the angle formed between the vector and a reference line. Refer again to figure 4-7. If the vector 0A in part (A) was 10 units in length, and θ was 45°, then vector 0A would be written in polar form as $10\,\angle 45^\circ$. The symbol $\angle$ means "at an angle of."

USE OF POLAR VECTORS

Polar vectors are used to identify a-c quantities in much the same manner as rectangular vectors. The major difference in the two forms is the symbolical method of representation. Note that when an impedance is represented in rectangular form, the components such as resistance and reactance are given, with overall impedance and phase angle implied. When the same impedance is represented in polar form, the overall impedance and phase angle are given, and the resistive and reactive components are implied.

Addition and Subtraction

Vectors expressed in polar form can be added or subtracted by graphical methods only, unless their directions are parallel. To add or subtract them algebraically, they must be converted to rectangular form. Conversion of one form to another is discussed later.

Multiplication

The product of two polar vectors is obtained by multiplying their magnitudes and adding their angles.

Example:

Multiply $8\angle 20^\circ$ by $20\angle -35^\circ$

Solution:

$$\begin{array}{r} 8 \\ \underline{20} \\ 160 \end{array} \qquad \begin{array}{r} 20^\circ \\ \underline{+(-35^\circ)} \\ -15^\circ \end{array}$$

$160\angle -15^\circ$ (answer)

Division

The quotient of two polar vectors is obtained by dividing their magnitudes and subtracting the angle of the divisor from the angle of the dividend.

Example:

Divide $30\angle 20^\circ$ by $2\angle 30^\circ$

Solution:

$$\frac{30}{2} = 15 \qquad \begin{array}{r} 20^\circ \\ \underline{-(30^\circ)} \\ 10^\circ \end{array}$$

$15\angle -10^\circ$ (answer)

CONVERSION OF FORMS

You have probably observed that certain forms of notation lend themselves more readily to one mathematical operation than to another.

For instance, the multiplying and dividing of rectangular vectors involve rather complex operations if compared to the multiplying and dividing of polar vectors. On the other hand, algebraic addition and subtraction of rectangular vectors involve relatively simple operations, whereas it cannot be done at all with polar vectors. Obviously, there are occasions when one form must be converted to the other. This is done in the following manner.

Rectangular to Polar Form

As previously stated, if rectangular members are considered to be two sides of a right triangle, then the hypotenuse and angle θ for any such triangle is directly implied by the given sides. To determine the value of the hypotenuse, you must first determine the angle θ. Angle θ is determined by first obtaining the value of its tangent, then locating this tangent value on a table of trigonometric functions. (There is a table of trigonometric functions in appendix IV of this book.) The tangent of angle θ can always be obtained by dividing the rectangular J member by the first, or energy, member.

For instance, to obtain the tangent of the angle implied by 3 + J4, divide J4 by 3. That is,

$$\tan\theta = \frac{4}{3}\text{, or } 1.33$$

If you locate the tangent value of 1.33 in the table of trigonometric functions, you will find that it is the tangent of 53.1°. You may state, then, that the angle θ for the vector 3 + J4 is 53.1°. After finding θ, the next step is to determine the length, or value, of the hypotenuse. This may be done in either of two ways. The hypotenuse is equal to the energy member divided by the cosine of 53.1°, or it is also equal to the J member divided by the sine of 53.1°. If 3 + J4 represented an impedance, then the hypotenuse (total impedance) could be written as follows:

$$Z = \frac{3}{\cos 53.1^\circ} \text{ or } Z = \frac{4}{\sin 53.1^\circ}$$

The numerical value of the sine or cosine of θ is obtained by consulting the table of trigonometric functions. Notice that the tangent, sine, and cosine for a given angle are all printed adjacent to one another. Since the cosine of 53.1° is 0.600, and the sine is 0.800, then

$$Z = \frac{3}{0.6} \text{ or } Z = \frac{4}{0.8}$$

In either case, Z = 5. Thus, when the rectangular vector $3 + J4\,\Omega$ is converted to a polar vector, it becomes $5\angle 53.1^\circ\Omega$.

Polar to Rectangular Form

This conversion is somewhat simpler, since angle θ is known at the start. In the polar vector $10\,\underline{/-53.1^\circ}$, the number 10 is considered to be the hypotenuse of a right triangle, and the angle θ is given as -53.1°. The implied remaining sides (rectangular members) are found as follows: The first (energy) member is found by multiplying the hypotenuse by the cosine of θ. The second, or J member, is found by multiplying the hypotenuse by the sine of θ. The algebraic sign of the resulting J member is the same as the sign of the given angle. The polar vector $10\,\underline{/-53.1^\circ}$ would thus be written in rectangular form as

$$(10 \times \cos 53.1^\circ) - J\,(10 \times \text{sine } 53.1^\circ)$$

or,

$$(10 \times 0.6) - (10 \times 0.8) = 6 - J8$$

APPLICATION OF RECTANGULAR AND POLAR NOTATION

As previously stated, a-c quantities represented in rectangular and polar form may be processed mathematically in that form, without direct use of trigonometric functions. Trigonometry will be used only if one form is converted to another.

It is important to note that these complex forms, when processed mathematically, are used in exactly the same manner, in relation to one another, as simple d-c quantities. For instance, suppose you were to solve an a-c problem involving an impedance of $2 - J3\,\Omega$, a current of $6 + J4$ amp, and a voltage of $24 - J10$ volts. Ohm's law states:

$$I = \frac{E}{Z}$$

or

$$E = I \times Z$$

and

$$Z = \frac{E}{I}$$

The same law applies in the solution of a-c problems, except that Z, I, and E are given in the more complex rectangular or polar forms. For instance (with all quantities given in complex form), since

$$\frac{E}{Z} = I$$

then

$$\frac{24 - J10 \text{ volts}}{2 - J3 \text{ ohms}} = 6 + J4 \text{ amp}$$

SOLUTION OF SERIES CIRCUITS

Assume that a voltage of $208 + J0$ volts is impressed on the series circuit shown in figure 4-11. Determine the following: (1) impedance, (2) current, and (3) phase angle.

Solution: Impedance is $60 + J80\Omega$ (1)

Since current is

$$I = \frac{E}{Z}$$

therefore,

$$I = \frac{208 + J0}{60 + J80}$$

$$= \frac{208 + J0}{60 + J80} \times \frac{60 - J80}{60 - J80}$$

$$= \frac{12{,}480 - J16{,}640}{10{,}000}$$

$$= 1.24 - J1.66 \text{ amp} \qquad (2)$$

The phase angle is determined by first obtaining its tangent as follows:

$$\tan\theta = \frac{-1.66}{1.24} = -1.33$$

The number 1.33, when located on the table of trigonometric functions indicates 53.1°. The minus sign indicates a -53.1°. Therefore,

$$\text{phase angle} = -53.1^\circ \qquad (3)$$

To determine (1), (2), and (3) in polar form, first convert the rectangular impedance $60 + J80\Omega$ into polar form.

$$\tan\theta = \frac{80}{60} = 1.33 = \text{tangent of } 53.1^\circ$$

$$\text{polar magnitude} = \frac{60}{\cos 53.1^\circ} \text{ or } \frac{80}{\sin 53.1^\circ} = 100$$

Therefore,

$$\text{polar impedance} = 100\,\underline{/53.1^\circ} \qquad (1)$$

Since

$$I = \frac{E}{Z}$$

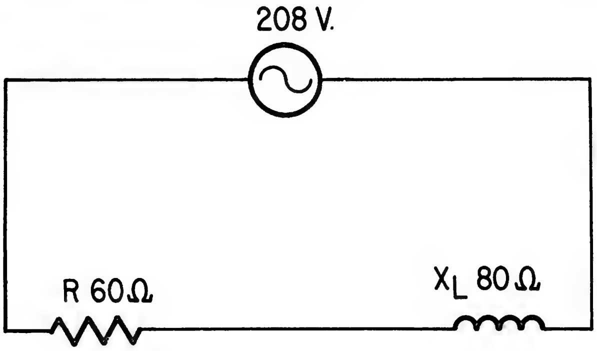

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Figure 4-11. — Simple series circuit.

then

$$I = \frac{208\angle 0°}{100\angle 53.1°}$$

$$= 2.08\angle -53.1° \qquad (2)$$

The phase angle has already been determined (-53.1°). (3)

DETERMINATION OF POWER

Power in a-c circuits may be calculated in much the same basic manner as in d-c circuits. That is, the basic mathematical relations still apply, in that $P = I \times E$, or that $P = I^2 \times Z$. The necessary inclusion of phase angle or power factor considerations is automatically accomplished by the use of rectangular notation. Since the voltages, currents, and impedances involved in power calculations are already divided into their energy and reactive components, then the solution of these calculations will yield an answer which is also divided into its energy and reactive components. That is, it will state the magnitude of both true power and VARS.

Before attempting power calculations, you should fix the following rule firmly in mind: When multiplying a voltage and current, you must use the conjugate of the voltage to obtain a correct answer. To obtain the conjugate of a rectangular vector, reverse the sign of the J operator. To obtain the conjugate of a polar vector, reverse the sign of the indicated angle. By using the conjugate of voltage, the algebraic sign of the J operator in the result will be of the proper type. That is, the power vector for an inductive circuit will have a -J, and a capacitive circuit will have a +J. This will be demonstrated during the following calculations.

For the circuit shown in figure 4-12, determine the following: (1) impedance, (2) voltage, (3) phase angle, (4) power factor, (5) true power, (6) VARS, and (7) apparent power.

Impedance is 30 - J40Ω. (1)

Since

$$E = I \times Z$$

then

$$E = (10 + J0) \times (30 - J40)$$

$$= 300 - J400 \text{ volts} \qquad (2)$$

$$\tan\theta = \frac{-400}{300}$$

$$= -1.33 = \text{tangent of } -53.1° \qquad (3)$$

$$\text{power factor} = \cos\theta \times 100$$

$$= (0.600 \times 100)$$

$$= 60 \text{ percent} \qquad (4)$$

$$\text{power is } P = E \times I$$

$$= (300 + J400) \times (10 + J0)$$

$$= 3{,}000 + J4{,}000 \text{ VA}$$

Therefore, true power = 3,000 watts. (5)

$$\text{VARS} = 4{,}000 \qquad (6)$$

apparent power (or total volt-amperes) =

$$\frac{\text{true power}}{\cos 53.1°} \text{ or } \frac{\text{VARS}}{\sin 53.1°} \qquad (7)$$

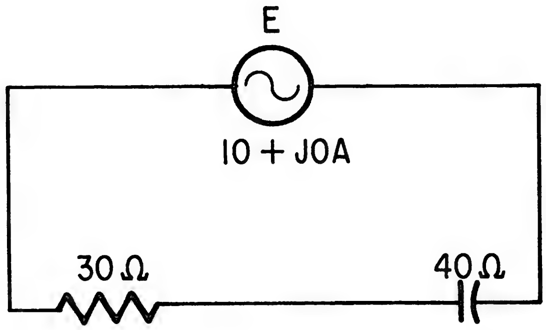

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Figure 4-12.—Series circuit for power calculation.

In either case, it is 5,000 VA. Note that reversal of the sign of the J operator in the voltage vector caused the sign of the J operator in the power vector to be plus. This is as it should be, since the circuit is capacitive. Had voltage and current been converted to polar form for multiplication, it still would have been necessary to conjugate the voltage. The rectangular voltage 300 - J400 converted to polar form would have been $500\underline{/-53.1^\circ}$ volts. Before multiplication it would have been conjugated to $500\underline{/53.1^\circ}$ volts. The solution for power would then have been $500\underline{/53.1^\circ}$ volts x $10\underline{/0^\circ}$ amp = $5{,}000\underline{/53.1^\circ}$ VA. Note that $5{,}000\underline{/53.1^\circ}$ VA is the correct polar form of 3,000 + J4,000 VA.

SOLUTION OF PARALLEL CIRCUITS

The mathematical relations and processes involved in the solution of a-c parallel circuits are identical in operation to those for d-c parallel circuits. The quantities are merely more complex. In d-c parallel circuits, total current is found by first determining and then combining all branch currents ($I_T = I_1 + I_2 + I_3$, etc.). Also, total resistance is found by combining the reciprocals of all branch resistances, and then determining the reciprocal of this combined quantity.

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

However, in a-c circuits, current will be given and used in complex form, and impedance (Z) will be given and used instead of resistance.

The circuit in figure 4-13 will be solved by determining currents first.

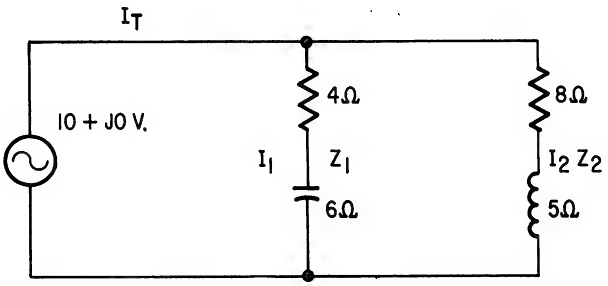

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Figure 4-13.—Parallel circuit for solution by currents.

$$I = \frac{E}{Z} \text{ in a-c}$$

Then

$$I_1 = \frac{10 + J0}{4 - J6}$$

$$= \frac{10 + J0}{4 - J6} \times \frac{4 + J6}{4 + J6}$$

$$= \frac{40 + J60}{52}$$

$$= 0.77 + J1.15 \text{ amp}$$

$$I_2 = \frac{10 + J0}{8 + J5}$$

$$= \frac{10 + J0}{8 + J5} \times \frac{8 - J5}{8 - J5}$$

$$= \frac{80 - J50}{89}$$

$$= 0.9 - J.56 \text{ amp}$$

Since

$$I_T = I_1 + I_2$$

then

$$I_T = (0.77 + J1.15) + (0.9 - J.56)$$

$$= 1.67 + J.59 \text{ amp}$$

With line voltage and total current known, circuit impedance may be determined.

$$Z_T = \frac{E}{I_T}$$

$$Z_T = \frac{10 + J0}{1.67 + J.59}$$

$$= \frac{10 + J0}{1.67 + J.59} \times \frac{1.67 - J.59}{1.67 - J.59}$$

$$= \frac{16.7 - J5.9}{3.13}$$

$$= 5.34 - J1.88\,\Omega$$

There would be little point in representing I_1 and I_2 in polar form, since they could not be combined in that form to obtain I_T. However, the division of voltage by impedance might have been facilitated by first converting these quantities to polar form, since polar vectors are more

easily divided than rectangular vectors. On the other hand, some time is required for this conversion. Consequently, the question of whether to convert or not depends on how well you are able to perform the conversion. You should use the quickest or most convenient method.

In the majority of cases, solution of parallel circuits by currents is the most feasible method. However, some problems require the determination of total impedance, when voltage is not given. In such cases, where neither voltage nor any branch current is known, I_T, or total current, cannot be determined. The circuit could be solved only to the extent of determining total impedance. This is done in a-c circuits by use of the same basic method used in d-c circuits. Where total resistance in d-c circuits is

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

total impedance in a-c circuits is

$$Z_T = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}}$$

When only two branches are considered in d-c,

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

Likewise in a-c circuits, total impedance is

$$Z_T = \frac{Z_1 \times Z_2}{Z_1 + Z_2}$$

If feasible, the reciprocal formula may also be used when solving two impedances.

Figure 4-13 is solved for total impedance using both methods mentioned. The reciprocal formula will be used first, assuming that line voltage is not given.

$$Z_T = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2}}$$

The reciprocal of each branch impedance must first be determined.

$$\frac{1}{Z_1} = \frac{1}{4 - J6}$$

$$= \frac{1}{4 - J6} \times \frac{4 + J6}{4 + J6}$$

$$= \frac{4 + J6}{52}$$

$$= 0.077 + J.115$$

$$\frac{1}{Z_2} = \frac{1}{8 + J5}$$

$$= \frac{1}{8 + J5} \times \frac{8 - J5}{8 - J5}$$

$$= \frac{8 - J5}{89}$$

$$= 0.089 - J.056$$

Combining reciprocals

$$\frac{1}{Z_1} + \frac{1}{Z_2} = (0.077 + J.115) + (0.089 - J.056)$$

$$= 0.166 + J.059$$

Total impedance is

$$Z_T = \frac{1}{0.166 + J.059}$$

$$= \frac{1}{0.166 + J.059} \times \frac{0.166 - J.059}{0.166 - J.059}$$

$$= \frac{0.166 - J.059}{0.031}$$

$$= 5.34 - J1.88\,\Omega$$

Since only two branches are involved, the second method of solution may also be used. Starting with the formula

$$Z_T = \frac{Z_1 \times Z_2}{Z_1 + Z_2}$$

then

$$Z_T = \frac{(4 - J6) \times (8 + J5)}{(4 - J6) + (8 + J5)}$$

The numerator is (4 - J6) x (8 + J5) = 32 - J28 - $J^2$30 = 62 - J28. The denominator is (4 - J6) + (8 + J5) = 12 - J1. Divide the numerator by the denominator as follows:

$$Z_T = \frac{62 - J28}{12 - J1}$$
$$= \frac{62 - J28}{12 - J1} \times \frac{12 + J1}{12 + J1}$$
$$= \frac{772 - J274}{145}$$
$$= 5.34 - J1.88\,\Omega$$

The impedance of the circuit has thus been solved in each of three ways: (1) by currents, (2) by the reciprocal formula, and (3) by the last method shown.

SOLUTION OF SERIES-PARALLEL CIRCUITS

Solution in Rectangular Form

The circuit shown in figure 4-14 is solved during the following explanation. Total current I_T, branch currents I_2 and I_3, total impedance, voltages E_1 and E_2, power, and phase angle are determined.

To obtain total current, total impedance must first be determined. Total Impedance is $Z_T = Z_1 \oplus (Z_2 \oplus Z_3)$, so the solution of $(Z_2 \oplus Z_3)$ must be completed first. The formula for two parallel impedances will be used:

$$Z_2 \oplus Z_3 = \frac{Z_2 \times Z_3}{Z_2 + Z_3}$$

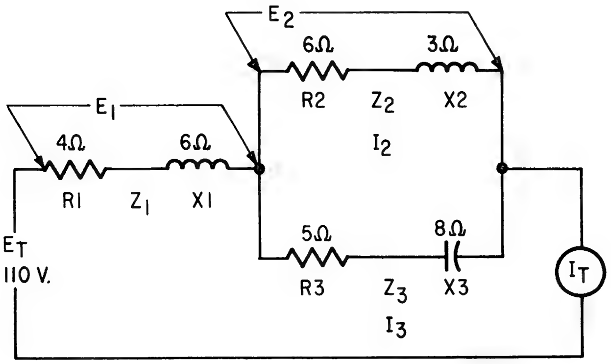

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Figure 4-14.—Series-parallel circuit.

The numerator $Z_2 \times Z_3$ is (6 + J3) x (5 - J8) = 54 - J33. The denominator is $Z_2 + Z_3$, or (6 + J3) + (5 - J8) = 11 - J5.

Insert these quantities in the formula for parallel impedance,

$$Z_2 \oplus Z_3 = \frac{54 - J33}{11 - J5}$$
$$= \frac{54 - J33}{11 - J5} \times \frac{11 + J5}{11 + J5}$$
$$= \frac{759 - J93}{146}$$
$$= 5.2 - J.64\,\Omega$$

Adding (5.2 - J.64Ω) to Z_1 (4 + J6Ω), total impedance Z_T is obtained.

$$Z_T = (5.2 - J.64) + (4 + J6)$$
$$= 9.2 + J5.36\,\Omega$$

Now that total impedance is known, and total voltage is given, total current I_T may be determined by the formula

$$I_T = \frac{E_T}{Z_T}$$

Insert the known values for E_T and Z_T; then

$$I_T = \frac{110 + J0}{9.2 + J5.36}$$
$$= \frac{110 + J0}{9.2 + J5.36} \times \frac{9.2 - J5.36}{9.2 - J5.36}$$
$$= \frac{1{,}012 - J589}{113.4}$$
$$= 8.92 - J5.19 \text{ amp}$$

Since the total current must flow through the series impedance Z_1, then the voltage E_1 may now be determined. $E_1 = Z_1 \times I_T$, or (4 + J6) x (8.92 - J5.19). E_1 = 66.8 + J32.6 volts. With E_1 known, E_2 is easily determined, because E_2 must equal E_T minus E_1. $E_2 = E_T - E_1$ = (110 + J0) - (66.8 + J32.6) = 43.2 - J32.6 volts. E_2 is the same across both parallel impedances Z_2 and Z_3, so the current through each may now be determined.

$$I_2 = \frac{E_2}{Z_2}$$

$$= \frac{43.2 - J32.6}{6 + J3}$$

$$= \frac{43.2 - J32.6}{6 + J3} \times \frac{6 - J3}{6 - J3}$$

$$= \frac{161.3 - J325}{45}$$

$$= 3.59 - J7.23 \text{ amp}$$

$$I_3 = \frac{E_2}{Z_3}$$

$$= \frac{43.2 - J32.6}{5 - J8}$$

$$= \frac{43.2 - J32.6}{5 - J8} \times \frac{5 + J8}{5 + J8}$$

$$= \frac{474.37 + J181.56}{89}$$

$$= 5.33 + J2.04 \text{ amp}$$

At this point, the solutions for voltages and currents may be checked before performing power calculations. To check, $E_1 + E_2$ should equal E_T; that is, $(66.8 + J32.6) + (43.2 - J32.6) = 110 + J0$ volts. Also, $I_2 + I_3$ should equal I_1, or I_T; that is $(3.59 - J7.23) + (5.33 + J2.04) = 8.92 - J5.19$ amp.

The power for the entire circuit is $P = E_T \times I_T$. That is, $P = (110 + J0) \times (8.92 - J5.19)$ VA. $E_T \times I_T = 980 - J572$ volt-amperes, which indicates a true power of 980 watts, and reactive volt-amperes of 572 VARS.

To solve for the phase angle θ, the tangent of θ is $J572 \div 980$, or 0.583. This is the tangent of 30.2°, which is the phase angle for the entire circuit. The cosine of 30.2° is 0.8643. This, when multiplied by 100, yields a power factor of 86.43 percent.

Solution in Polar Form

The solution for currents and voltages in figure 4-14 can also be performed by the use of polar quantities. To do this, the first step is to convert all rectangular quantities to their polar form. At the same time, you must retain the rectangular quantities, because total impedance must be determined first, and rectangular quantities must be used to do this. Rectangular quantities will also have to be used in various other processes, as you will see during the course of solution.

Total impedance Z_T was determined to be $9.2 + J5.36\,\Omega$, and E_T is given as $110 + J0$ volts. If polar form is to be used for solving total current I_T, then E_T and Z_T must be converted to polar form. Z_T is converted as follows:

$$\frac{5.36}{9.2} = \tan\theta$$

$$= \tan 30.2°$$

The polar angle of Z_T is 30.2°. Then the polar magnitude of Z_T is

$$\frac{5.36}{\sin 30.2°} \text{ or } \frac{9.2}{\cos 30.2°}$$

Either method you prefer may be used. In either case, its magnitude is 10.65. The complete polar form of Z_T is $10.65\angle 30.2°\,\Omega$. E_T in polar form is $110 \div 0°$ volts. Total current is

$$I_T = \frac{E_T}{Z_T}$$

$$= \frac{110\angle 0°}{10.65\angle 30.2°}$$

By dividing magnitudes and subtracting angles, I_T is determined to be $10.32\angle -30.2°$ amp.

The next quantity to be determined is E_1. If this is done in polar form, Z_1 must first be converted to polar form before multiplying by I_T. The tangent of angle θ for Z_1 is $J6 \div 4$, or 1.5, the tangent of 56.3°. Determining the polar magnitude

$$Z_1 = \frac{6}{\sin 56.3°}, \text{ or}$$

$$= \frac{4}{\cos 56.3°}$$

$$Z_1 = 7.2$$

$$Z_1 = 7.2\angle 56.3°$$

$$E_1 = Z_1 \times I_T$$

$$= 7.2\angle 56.3° \times 10.32\angle -30.2°$$

Multiplying magnitudes,

$$(7.2) \times (10.32) = 74.3,$$

combining angles

$$(56.3°) + (-30.2°) = 26.1°$$

then

$$E_1 = 74.3 \angle 26.1° \text{ volts}$$

To determine E_2, E_1 is subtracted from E_T. Since polar quantities cannot be subtracted algebraically, E_T and E_1 are reconverted to rectangular form. The rectangular forms of E_T and E_1 have already been determined. Their difference is E_2. E_2 was determined to be 43.2 - J32.6 volts. If I_2 is to be expressed in polar form, then E_2 and Z_2 must first be converted to polar form, since I_2 is E_2/Z_2. The same applies to the solution for I_3. That is, Z_3 would also have to be converted to polar form, because I_3 is E_2/Z_3.

The calculation for power and phase angle is relatively simple, since the polar forms of E_T and I_T are known, and can be multiplied in that form.

$$(P = E_T \times I_T \text{ VA})$$

Solving for power:

$$(110 \angle 0°) \times (10.32 \angle -30.2°) = 1{,}133 \angle -30.2° \text{ VA}$$

This indicated quantity may be checked against the indicated rectangular quantity 980 - J572 VA as follows:

$$1{,}133 \times \cos(-30.2°) = (1{,}133) \times (0.866)$$
$$= 980 \text{ watts}$$

Also,

$$1{,}133 \times \sin(-30.2°) = (1{,}133) \times (-0.503)$$
$$= -572 \text{ VARS}$$

It will be noted that the use of polar vectors to solve the circuit in figure 4-14 required frequent conversion of polar vectors to rectangular vectors. These conversions were necessary due to the difficulty in adding or subtracting quantities expressed in polar form, and considerable time and effort is needed for these conversions. Consequently, it will usually be to your advantage to employ rectangular quantities, rather than polar quantities, since the rectangular form is not subject to any such mathematical limitation.

CHAPTER 5

ADVANCED ALTERNATING-CURRENT THEORY—CONTINUED

POLYPHASE POWER SYSTEMS

ADVANTAGES OF POLYPHASE SYSTEMS

In recent years, the a-c power systems in naval aircraft have assumed greater importance as part of the aircraft's functioning equipment. The trend in electrical power systems is away from direct-current systems and toward alternating-current systems. More specifically, the trend is almost entirely toward polyphase a-c systems for the generation and distribution of electrical power.

The weight-to-performance ratio is of prime importance in the design of all airborne equipment, and this applies to electrical power components as well. This fact has a direct bearing on the reasons for using polyphase systems instead of single-phase systems. A 3-phase a-c generator or inverter of given weight and dimensions may have up to a 60 percent greater power rating than a single-phase machine of the same physical size and weight. This same approximate power rating applies also to a-c motors.

Another important consideration is the conductor weight of the distribution system. To conduct equal amount of power, the 3-phase system requires only about 75 percent of the copper weight which would be required for a single-phase system.

Also, the pulsating load on a single-phase a-c generator is reflected in continuous pulsations of the mechanical drive shaft speed and torque. In a 3-phase generator, individual phase power is pulsating, but the total power of all three phases is more constant if the load is balanced. Consequently, the generator drive shaft speed and torque are relatively constant.

DOUBLE SUBSCRIPT NOTATION

In working with problems which involve more than one voltage or current, it is best to employ a systematic means of identification for referring to these voltages and currents. One method for doing this is the use of letters used as subscripts. For instance, the currents in a parallel circuit of three branches might be referred to as I_A, I_B, and I_C. By using a double subscript (two letters), direction as well as identity may be established for a quantity. Suppose the three parallel branches mentioned are connected to a common bus, or point, identified as point O. The three currents, if they were all flowing toward point O, could then be referred to as I_{AO}, I_{BO}, and I_{CO}. Conversely, if all currents were flowing away from point O, then a reversal of direction would be indicated by reversing the currents' subscripts. In this case, they would be I_{OA}, I_{OB}, and I_{OC}.

This system of notation may be applied equally well to voltages, since voltage is assumed to act in a certain direction. As with current, the direction of a voltage may be indicated by the sequence of its subscript.

When voltages or currents are represented in equations, their algebraic direction may be represented by the sequence of their subscripts as well as their algebraic sign. This relation will be shown by referring to the voltages in the circuit shown in figure 5-1 (A).

Total circuit voltage E_{AD} is obviously comprised of the segment voltages E_{AB}, E_{BC}, and E_{CD}. This fact could thus be stated in the form of an equation as follows:

$$E_{AD} = E_{AB} \oplus E_{BC} \oplus E_{CD}$$

Since the segment voltages are vector quantities, they must be added as vectors. Assume the segment voltages have individual phase angles as shown in part (B) of figure 5-1. Part (B) also shows how the successive combining of vectors produced E_{AD}. Note that all vectors are acting in an A toward D direction.

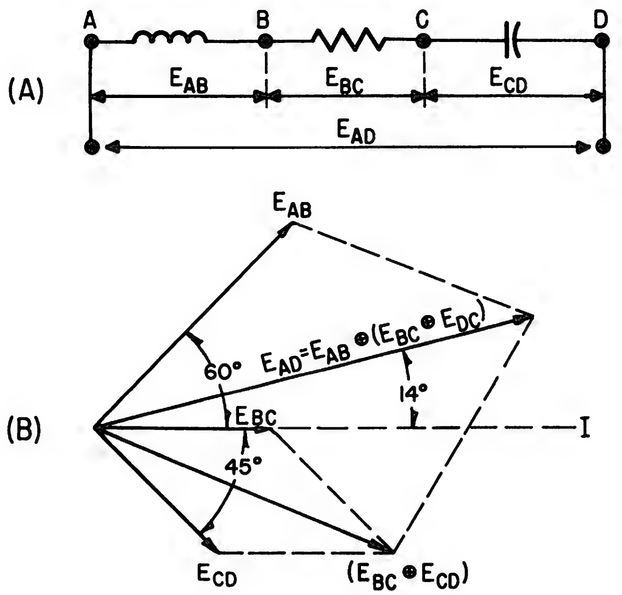

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Figure 5-1.—(A) Circuit segment voltages; (B) segment voltage vectors.

Since E_{AD} is composed of the segment voltages shown, it follows that E_{AD} minus all segment voltages would equal zero. In equation form, after transposing and changing the signs of the segment voltages, E_{AD} is equated to zero as follows:

$$E_{AD} \oplus (-E_{AB}) \oplus (-E_{BC}) \oplus (-E_{CD}) = 0$$

It must be remembered that to subtract vectors, one vector is reversed, and then the two are added. Since all segment voltage vectors are to be subtracted from E_{AD}, all of them are reversed. By reversing subscripts the equation $E_{AD} \oplus (-E_{AB}) \oplus (-E_{BC}) \oplus (-E_{CD}) = 0$ can be simplified as follows: $E_{AD} \oplus E_{BA} \oplus E_{CB} \oplus E_{DC} = 0$. To prove this equation correct, the successive vector subtraction of segment voltages from E_{AD}, as indicated in the equation, is carried out in figure 5-2.

In part (A), E_{AB} is reversed to E_{BA} and added to E_{AD}, obtaining $E_{AD} \oplus E_{BA}$. In part (B), E_{CD} is reversed to E_{DC} and added to $(E_{AD} \oplus E_{BA})$, obtaining $(E_{AD} \oplus E_{BA} \oplus E_{DC})$. Note in part (C) that this quantity lies exactly along E_{BC}, so that when E_{BC} is reversed to E_{CB}, the result is zero. This proves, by direct vector analysis, that showing vector directions by subscripts is a method of representation which is both accurate and simple, when these vectors appear in mathematical equations. The use of double-subscript notation is particularly effective in separating and identifying polyphase voltages and currents when these quantities are represented as vectors.

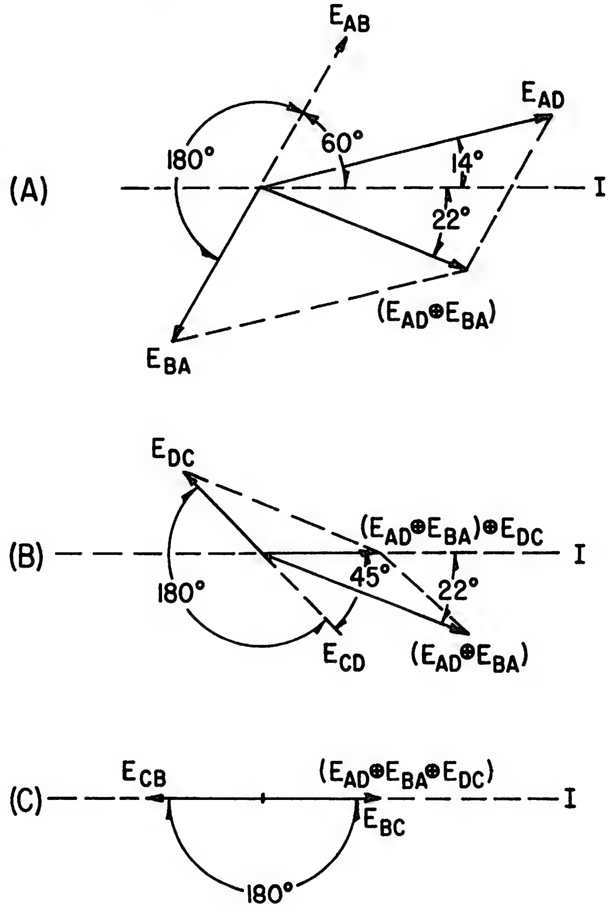

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Figure 5-2.—Subtraction of voltage vectors.

GENERATION OF POLYPHASE VOLTAGES

The 3-phase a-c power system is by far the most commonly used of any polyphase system. For this reason, only the 3-phase system is discussed in this chapter.

Alternating-current generators and inverters are manufactured in a variety of sizes, shapes, and ratings. These vary in appearance and performance from tiny synchro signal generators to the relatively huge a-c generators installed aboard certain large aircraft. However,

practically all these machines have some features in common. They usually have a rotating field of fixed polarity and a stationary armature. No matter what the size or complexity of these machines, they may be simplified for purposes of explanation to the forms shown in figure 5-3.

The field is reduced to a simple rotary 2-pole magnet, and the armature windings are reduced to three simple coils fixed 120 electrical degrees apart. Note that dashed lines extend end-to-end through the field and all three coils. The dashed lines through the coils will be referred to as "coil planes," and the dashed line

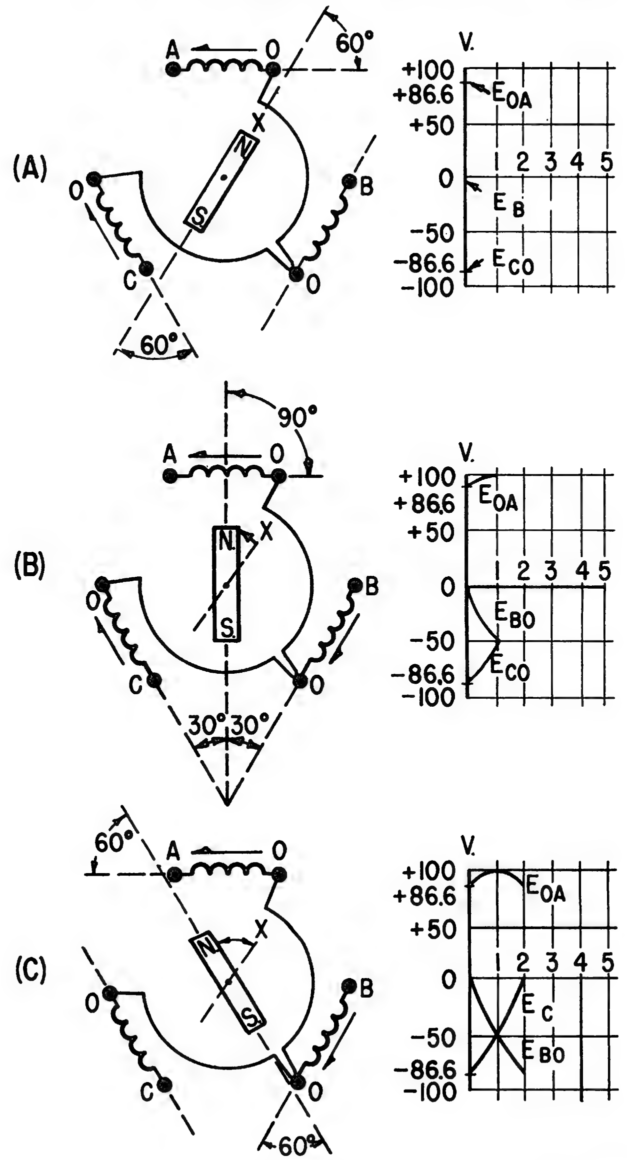

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Figure 5-3.—Generation of 3-phase sine waves.

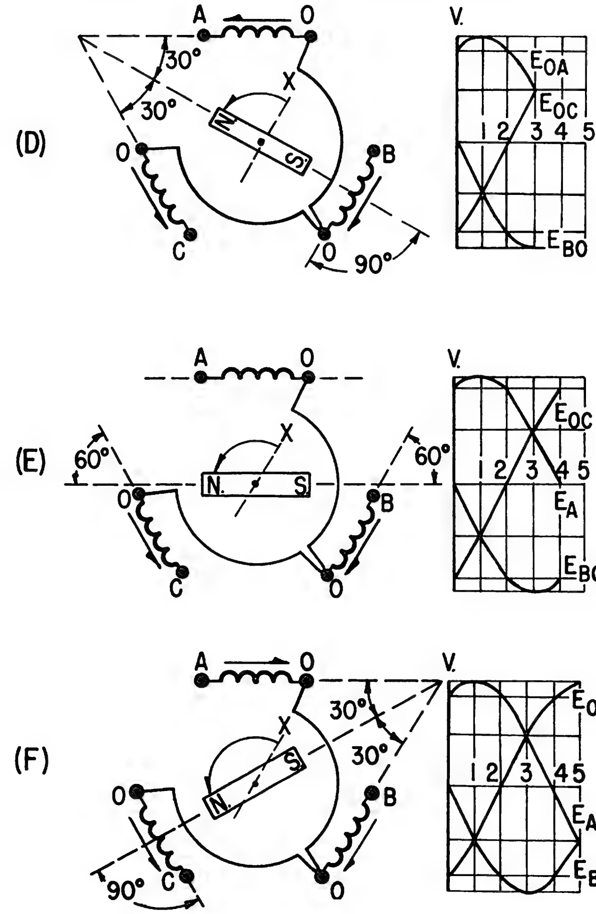

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Figure 5-3.—Generation of 3-phase sine waves—Continued.

through the field will be referred to as the "field plane." The coils are labeled A, B, and C, and corresponding coil ends are connected to form a common reference point labeled O. It is assumed that the coils are wound so that when the north field pole is adjacent to any coil, the direction of induced voltage is away from point O and toward the lettered end of that coil. This voltage direction is referred to as "positive." A positive voltage may thus be identified by the order of its subscript (E_{OA}, E_{OB}, or E_{OC}). It follows that when the south field pole is adjacent to any coil, the direction of induced voltage is "negative"; that is, from the lettered end toward the common end. Again, the direction is indicated by the order of subscripts. Negative voltage would be E_{AO}, E_{BO}, or E_{CO}. Peak voltage in the coils is 100 volts.

At the starting instant shown in part (A) of figure 5-3, the field plane lies along an axis labeled X. At this instant, it can be seen that the field plane is at 60° to the plane of coil A. Consequently, the instantaneous voltage in coil A is 100 x sin 60° = 100 x 0.866 = 86.6 volts. The north field pole is adjacent to coil A, so its induced voltage is positive. This value is indicated as + 86.6 (E_{OA}) on the sine graph to the right of the drawing. The plane of coil B is parallel (0°) to the field plane, so its voltage is zero. Coil C is at 60°, but adjacent to the south field pole, so its instantaneous voltage (E_{CO}) is negative, -86.6 volts, as shown on the sine graph.

In part (B) of figure 5-3, the field has been rotated 30° away from the X axis. It can be seen that all three coil voltages have undergone simultaneous changes in accordance with the changes of their coil plane angles with respect to the field. These changes are traced as the beginning of sine waves on the graph. E_{OA} increased from 86.6 volts to 100 volts. E_B started in a negative direction, becoming E_{BO}, and increased to -50 volts. E_{CO} decreased from -86.6 volts to -50 volts.

Parts (C), (D), (E), and (F) of figure 5-3 show successive changes in the coil voltages. These changes are caused by additional rotation of the field. The progressive development of sine waves may be observed on the sine graphs. All parts of figure 5-3 should be studied carefully, since it illustrates the fundamental manner in which practically all 3-phase voltages are generated.

Figure 5-3 traces the development of sine waves only through five steps of 30° each, for the total field rotation of 150°. If the development were continued for a full 360°, the sine graph would appear as shown in figure 5-4.

Where the field in figure 5-3 started at the X axis and rotated 150°, the same field as represented by arrows is considered to have rotated 360° when shown in figure 5-4.

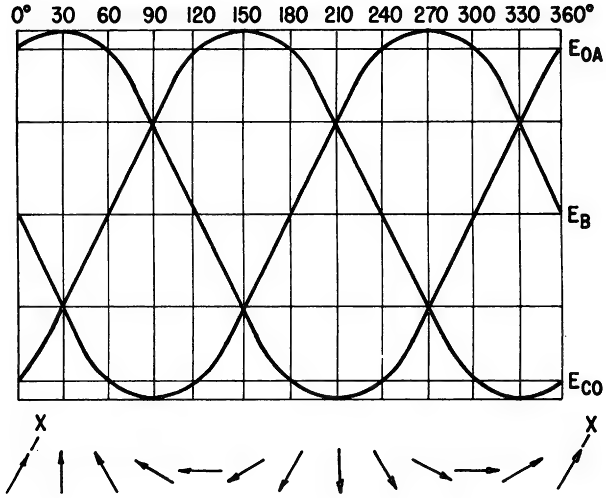

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Figure 5-4.—360° development of 3-phase sine wave.

VECTORS OF 3-PHASE VOLTAGE

The methods used in figures 5-3 and 5-4 suffice to show how 3-phase voltages are generated and their sine waves are formed. Also, the instantaneous magnitude and direction of any phase voltage, for a given field position, is easily determined by observing the sine graph. However, the drawing and construction of the sine graph itself is a laborious process. A more practical and convenient method for representing 3-phase voltages involves the use of rotating vectors of the type shown in figure 5-5 (A). Note that these vectors are laid out in such a way as to coincide with the three coil positions shown in part (B).

For ease of explanation, the a-c generator in part (B) has a fixed field and rotary coils. Regardless of which member is rotating, instantaneous coil voltage is still determined by the angle between field plane and coil plane. Any coil lying to the right of the Y axis will have a positive direction of induced voltage, or away

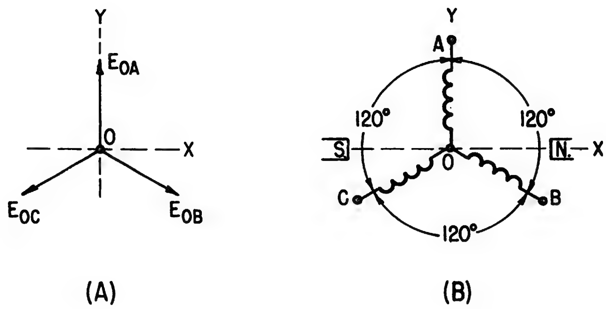

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Figure 5-5.—(A) Three-phase vector; (B) corresponding coil positions.

from terminal O. A coil lying to the left would have a negative voltage. Peak voltage in a coil would exist when it lies exactly along the X axis (peak positive to the right, and peak negative to the left). If the peak value of coil emf's were represented by the length of the rotary vectors in part (A), then instantaneous voltage direction could be determined by observing on which side of the Y axis a particular vector is lying. Further, in addition to direction, its instantaneous magnitude is determined by the angle (θ) between the vector and the X axis. That is, $e = E \times \sin \theta$, where e is instantaneous voltage, E is peak voltage, and θ is the instantaneous angle between a particular vector and the X axis.

In addition to determining individual phase voltages, vectors may also be used to determine the voltage between two conductors, where each conductor is connected to a different phase coil. Figure 5-6 will be used to demonstrate that this voltage (line-to-line voltage) is the difference of the phase coil voltages. To obtain line-to-line voltage from two such coils, the leading phase is subtracted algebraically from the lagging phase. In figure 5-6 (A), assuming a CCW rotation, coil B leads coil A. (Coil C is disregarded, since it contributes nothing to E_{AB}.) The line-to-line voltage must be E_{AO}

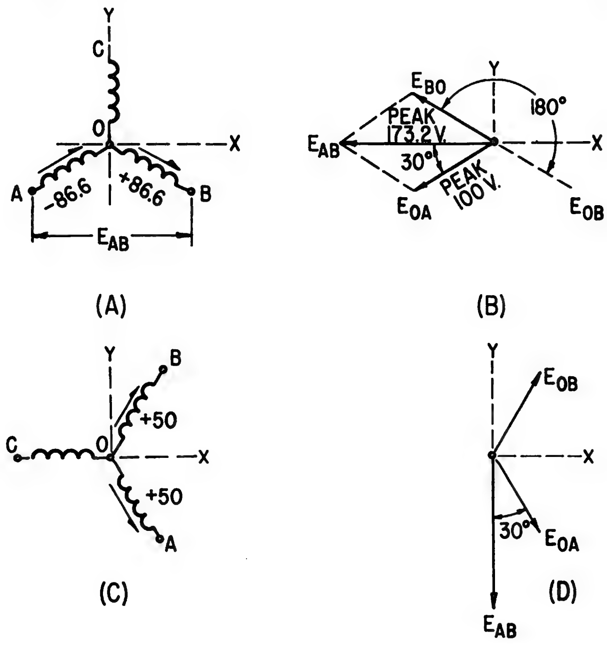

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Figure 5-6.—Combining polyphase voltages by vectors.

$-E_{OB}$ or -86.6 - (+ 86.6). Dropping the parenthesis and changing the sign within, $E_{AB} = -86.6 - 86.6 = -173.2$ volts.

WYE-CONNECTED SYSTEMS

VOLTAGES IN A WYE SYSTEM

The wye connection for a 3-phase system is one in which an end of each phase is connected to a common junction. It is probably apparent by now that this type of connection affects system voltages in ways peculiar to itself.

If the same operation were carried out vectorially, the usual rules for subtracting vectors would apply. Referring to figure 5-6 (B), vector E_{OB} is leading, and is therefore the subtrahend. To subtract EOB from E_{OA}, EOB is reversed 180° as shown, and then added to E_{OA}. The result is E_{AB}. Note that E_{AB} lies exactly along the X axis, and is also to the left of the Y axis. This means that at the instant shown in both (A) and (B), the line-to-line voltage is at its negative peak value. If vectors E_{OA} and E_{OB} are considered to be 100 units long, then E_{AB} is 173.2 units long. That is, the peak value of line-to-line voltage E_{AB} is 173.2 volts. Parts (A) and (B) are thus seen to be in complete agreement.

In part (C) of figure 5-6, the coils have been rotated so that both lie to the right of the Y axis, and are equal distances from the X axis.

Consequently, both have positive and equal voltages. In this case, E_{AB} is obviously zero. This is proven as follows:

$$E_{AB} = +50 - (+50) = +50 - 50 = 0 \text{ volts.}$$

This agrees with the vector representation as shown in part (D). Note that vector E_{AB} lies exactly along the Y axis, indicating a magnitude of zero.

Figure 5-7 depicts a 4-wire, 3-phase system of the type most commonly used in naval aircraft. In addition to the 3-phase conductors, a fourth conductor is brought out from the common junction. This conductor is most commonly referred to as "neutral." Voltage V_2 in figure 5-7 (A) is taken between the phase-line A and neutral. This is known as "line-to-neutral" voltage, and is obviously equal only to the voltage of the phase across which it is taken. Voltage V_1 is a "line-to-line" voltage. As shown in (B) of figure

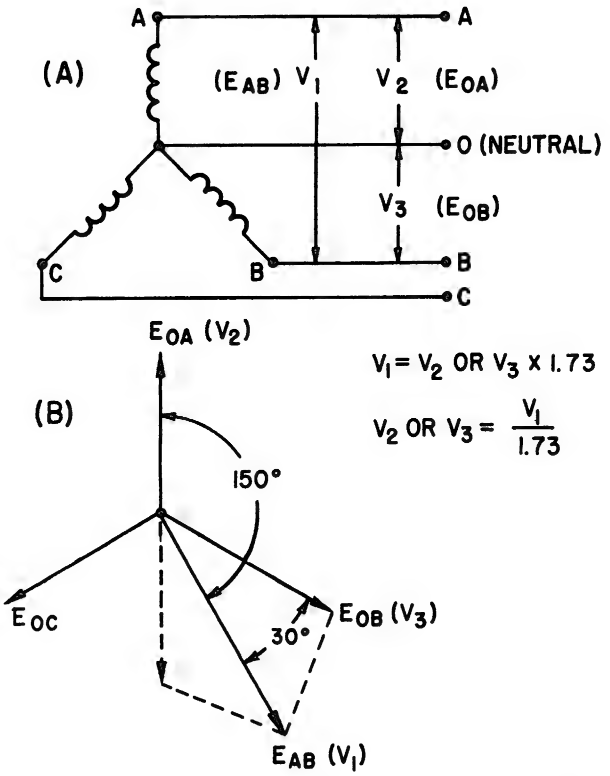

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Figure 5-7.—Voltages in wye-connected 3-phase system.

5-6, the line-to-line voltage of two coils 120° apart is equal to either coil's voltage times 1.73. It can be stated that in figure 5-7, $V_1 = V_2$ or $V_3 \times 1.73$ ($1.73 = \sqrt{3}$). This relation is true for all wye-connected 3-phase systems under balanced load conditions. That is, line voltage E_L is equal to coil (phase) voltage E_C times $\sqrt{3}$ or ($E_L = E_C \times 1.73$). This is true, using either effective coil voltage or peak coil voltage. However, the resultant line voltage will also be of corresponding effective or peak value. Conversely, if line voltage E_L is known, coil voltage is:

$$E_C = \frac{E_L}{1.73}$$

An additional characteristic of wye voltages is shown in (B) of figure 5-7. It can be seen that any line-to-line voltage lags one of its phase voltages by 30° and the other phase voltage by 150°. This would be true for any two combined phase voltages, such as the combining of V_2 and V_3 to produce V_1.

CURRENTS IN WYE SYSTEMS

Figure 5-8 (A) shows a wye-connected 3-phase generator supplying a balanced load. Each load resistor is 100 ohms, and all three resistors are connected in wye. The generator voltages (emf's) are designated by the letter E, and the load voltages by the letter V, as is customary. The sum of the emf's at terminal O can be seen as being equal to zero. Also, the sum of the load voltages at terminal O' is also zero. Thus it follows that there is no difference in potential between O and O'.

Figure 5-8 (B) shows that the sum of the currents entering and leaving terminals O and O' are also equal to zero. Since no potential difference exists between terminals O and O', no current flows between them. This condition is true only when the system is balanced, and a system is balanced only when the following conditions exist:

1. All phase emf's are equal.
2. All phase load impedances are equal. (They may be reactive, but are considered balanced when each has the same reactive characteristic and power factor.)
3. All phase currents are equal.

The loads in figure 5-8 are not reactive, so the current and voltage of each resistor are in

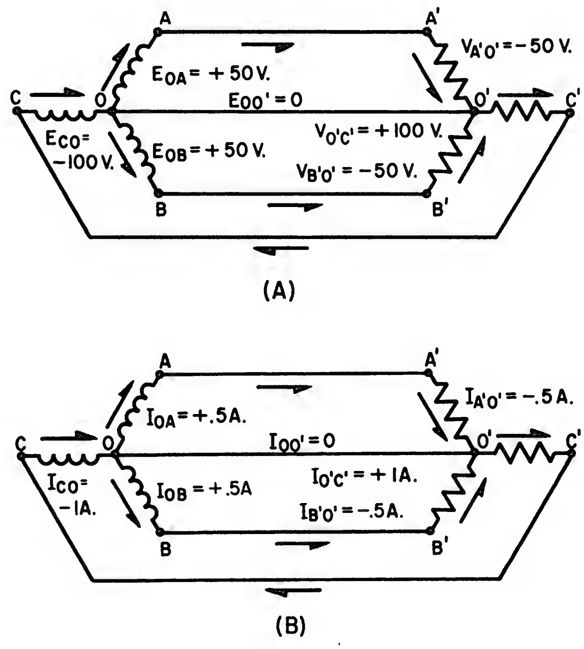

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Figure 5-8.—Currents in a wye system.

phase. Consequently, the coil currents and generated emf's in the generator must also be in phase. Since it has already been established that the voltage of any wye line lags by 30° the voltage of the phase coil to which it is connected, then it follows that this line voltage also lags the coil current by 30°. This is true for a balanced system. That is, the 30° difference between line current (same as coil current) and line voltage in a wye-connected system is merely another wye system characteristic. It must not be confused with phase differences caused by reactive or unbalanced resistive loads. Reactive loads may cause line current to be out of phase with coil voltage as well as with line voltage.

Figure 5-9 (A) is the vector diagram of a generator supplying a nonreactive (resistive) load. Note that each phase current is in phase with its coil voltage, and that each line voltage is 30° out of phase with its coil voltage. This is as they should be. In part (B), assume the same generator is represented but that its load has been changed from a balanced resistive to a balanced inductive load. The inductive nature of the load phases will cause their currents to lag their voltages by the angle θ. This same lag is reflected automatically in the generator coils, since coil current, line current, and load current for a given phase are one and the same in a wye system. The lag for all three phases is the same, since it was assumed that the load is balanced. That is each load phase has the same inductance. Part (B) thus shows how the coil current in the generator may be moved out of phase with coil voltage, by the type of load placed on the generator. (It is significant to note at this point that a capacitive load would have caused leading coil currents in figure 5-9.)

Regardless of load characteristics, any reference made to the power factor of a three-phase system refers to the phase angle between coil voltage and coil current. If line voltage rather than coil voltage were used as a reference, the factor $\theta - 30°$ or $\theta + 30°$ would have to be taken into consideration. Also, when an unbalanced condition exists, each phase may have a power factor angle different from the others, so that power must be computed for each phase separately to obtain total power. Under these circumstances, the term "system power factor" would be meaningless.

POWER IN WYE SYSTEMS

When an a-c generator or inverter is supplying a load, the total power being supplied is the sum of the power in all three phases. If the load is balanced, then the power being supplied by each generating coil is the same, and total power is $P_T = P_C \times 3$, where P_C is the power in any phase, or coil. The power (apparent) for any coil is $P_C = E_C \times I_C$, where E_C is coil emf and I_C is coil current.

Line power (the same as total power) is determined by computations based on line voltage and current, rather than coil voltage and current. Total power expressed in terms of coil voltage and current is:

$$P_T = 3 \times E_C \times I_C$$

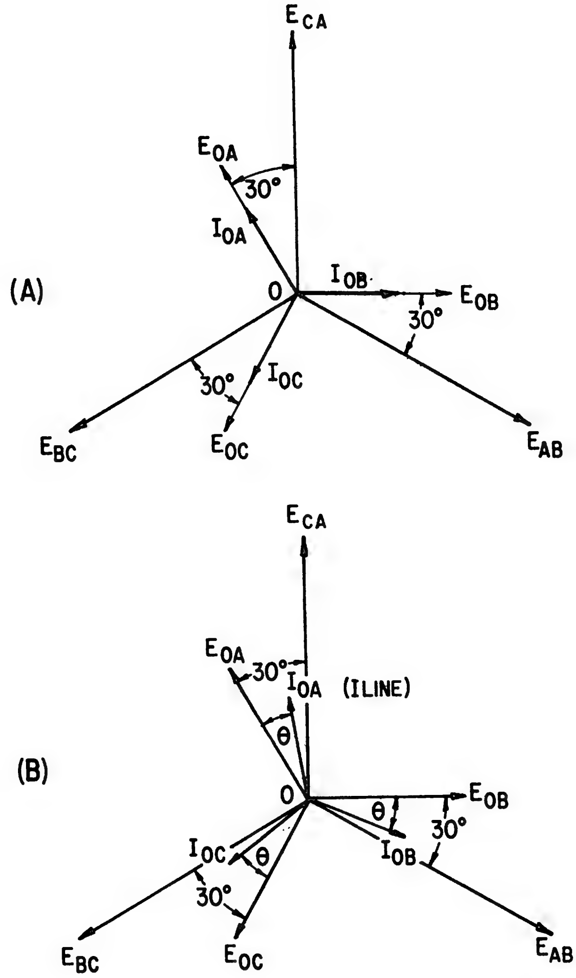

Figure 5-9.—(A) Balanced resistive load vectors; (B) balanced reactive load vectors.

If power is to be expressed in terms of line voltage E_L and line current I_L, these quantities are substituted in the same formula, as follows:

$$E_C = \frac{E_L}{1.73}$$

also

$$I_L = I_C$$

Substituting

$$P_T = 3 \times \frac{E_L}{1.73} \times I_C = 1.73 \times E_L \times I_L$$

When a 3-phase system is balanced, it can be seen that total power may be expressed in terms of line voltage and current, since all three respective values are equal, and it is assumed that individual phase powers are equal. However, in an unbalanced condition, individual phase powers are expressed separately, since each may have a power different from the others. Obviously, individual coil voltages and currents would have to be used. Total power in unbalanced systems would then be the sum of the individually determined phase powers.

When a balanced system is reactive, the power factor of the system must be used to indicate total true power, after total volt-amperes is determined. Assuming that the system is balanced, then the power factor angle θ is the same for all phases. This angle is considered to be the system power factor angle. Using line values for voltage and current in a reactive system, the formula $P_T = 1.73 \times E_L \times I_L$ will produce total volt-amperes. The total true power in watts is $P_{TP} = 1.73 \times E_L \times I_L \times \cos\theta$, which takes the system power factor into consideration.

When a system is both reactive and unbalanced, there is no such thing as a system power factor unless such a term is used to refer to the average of the individual phase angles. As stated before, total power in an unbalanced system is the sum of the power in all the phases. The solution of unbalanced systems will be discussed later in this chapter.

DELTA-CONNECTED SYSTEMS

VOLTAGES IN A DELTA SYSTEM

Figure 5-10 (A) shows a wye-connected generator with typical instantaneous values of coil emf. Assume that the three voltmeters are capable of measuring instantaneous values of voltage. It can be seen that each voltmeter indicates the combined emf of two coils, because each pair of lines is connected across the ends of two coils.

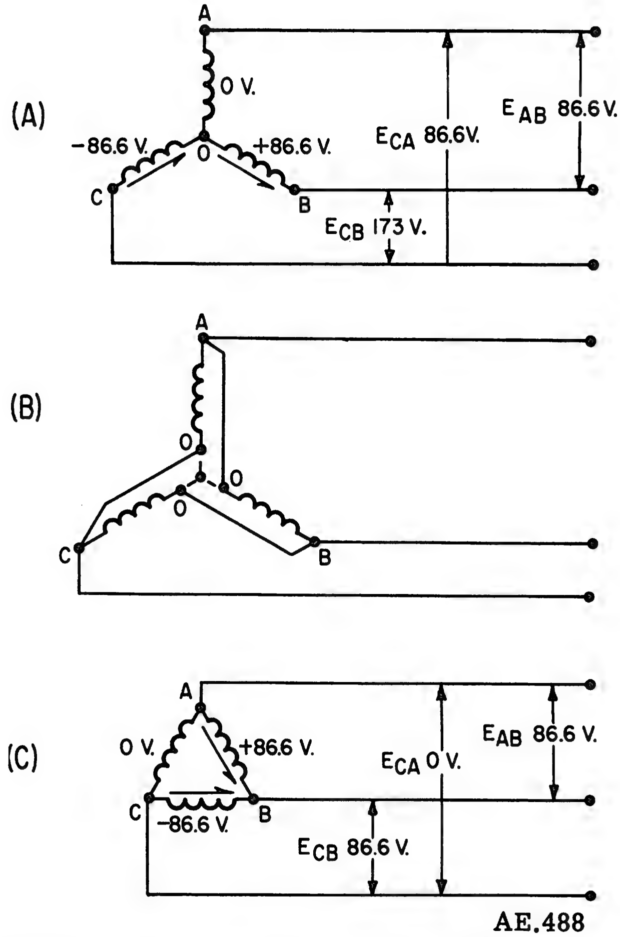

Figure 5-10.—Comparison of wye voltages to delta voltages.

In (B) of figure 5-10, the common coil ends are disconnected from each other, and these same coil ends are then reconnected by jumpers, as shown, to the outer ends of adjacent coils. Since any two points connected by a jumper are electrically the same, these two points may be joined directly, as shown in (C), and the jumper is eliminated. The generator is now connected in delta.

The instantaneous emf's are the same in each generator coil in (C) as they were in (A). Only the coil interconnection has been changed in the generator. On the lines, however, significant changes in voltage have taken place, as shown by the voltmeters. These changes take place

because each pair of lines is now connected across a single coil, rather than a pair of coils. This shows that, unlike wye-line voltages, the line-to-line voltage in a delta-connected system is always the same as the coil voltage; that is, $E_L = E_C$.

It might seem at a glance that the line-to-line voltage across a particular delta coil would be affected by the emf's in the remaining two coils, since the pair is connected at each end to the same points across which voltage is being measured. This is not true, however, because the instantaneous magnitude and direction of emf in a particular coil is always equal and opposite to the sum of the emf's in the remaining two coils. Therefore, the measurable effect of the emf's in the remaining two coils is zero. This may be seen more clearly when you consider the voltmeter reading E_{CA} in (C) of figure 5-10. The induced emf in coil AC is zero. Also, the sum of the emf's E_{AB} and E_{CB} is zero. Therefore, any voltage measured across the coil AC is considered to be a voltage induced into that coil as a function of the generator. In a balanced delta system, no current will be impressed through a particular coil by the remaining two coils, but will flow as a result of its own induced voltage.

Because the emf in a particular coil is equal to the sum of the emf's in the remaining two coils ($E_{AB} \oplus E_{CB} = 0$) then it follows that the sum of all three emf's around the delta loop is zero at all times ($E_{CA} \oplus E_{BA} \oplus E_{BC} = 0$). This is shown in figure 5-11 where the coil connections at point A are broken to form points A and A'. If a voltmeter were connected between these points as shown, it would indicate zero at all times, provided each coil is identical to the other. As a matter of fact, this is referred to as "closure voltage," and is one of the final items to be checked before the final connection is made when it is desired to operate a transformer or a-c generator in delta. That is, should a voltage equal to coil voltage or more exist from A to A' it would indicate that the coil is reversed. Correction would have to be made before making the final connections, or "closure" of the delta, to avoid short circuit current flow.

CURRENTS IN A DELTA SYSTEM

Figure 5-12 (A) represents a delta-connected generator with coil currents whose peak value is 10 amperes. Coils AC and CB are both at 60° from the zero Y axis, so their instantaneous

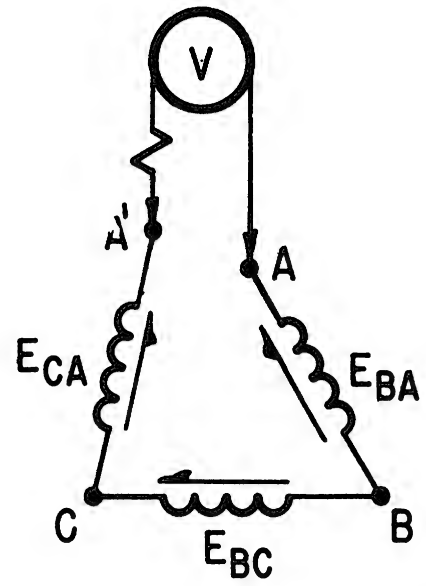

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Figure 5-11.—Measurement of sum of delta loop voltages.

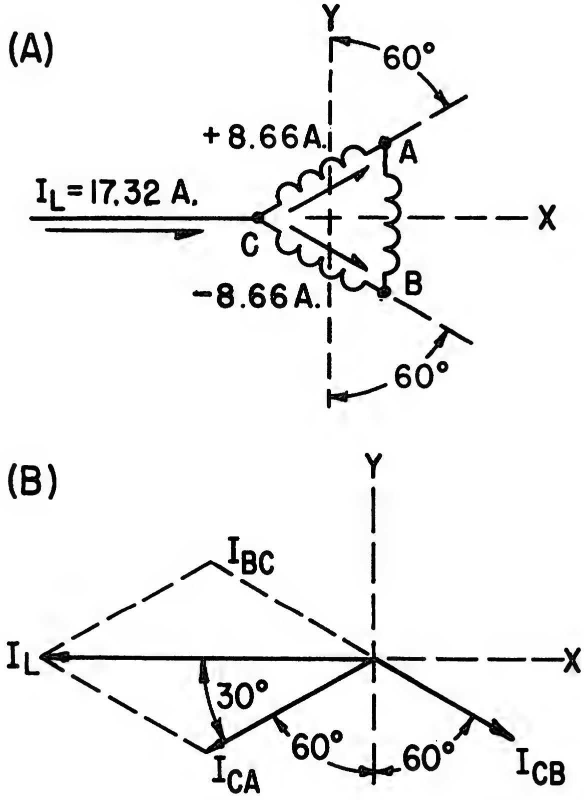

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Figure 5-12.—Currents in the delta connection.

currents are of the magnitude shown (10 x sin 60° = 8.66 amp). Since the two currents are acting in opposite directions around the delta loop, they are given opposite algebraic signs. In this explanation, coils lying above the X axis will have positive voltages and currents, while those lying below the X axis will have negative values.

The current carried by a delta line (I_L), such as the one connected to terminal C in figure 5-12 (A), is equal to the difference of the currents in the two coils to which the line is connected. Thus, in figure 5-12, the line current is $I_L = I_{CA} - I_{CB} = +8.66 - (-8.66)$ amp. Removing the parenthesis, changing the sign within, and combining terms, line current is $+8.66 + 8.66 = 17.32$ amperes. Note that the value for the leading phase current (I_{CB}) is the subtrahend. Figure 5-12 (B) is a vector representation of the instantaneous conditions shown in (A). The two coil current vectors, I_{AC} and I_{CB} are each 60° from the zero X axis, which corresponds to the coil positions shown in (A). Coil CB is leading, so its current vector is the subtrahend and must be reversed. When I_{CB} is reversed to I_{BC} and added to I_{CA}, the resultant is I_L. The length of vector I_L is 1.732 times the length of either coil current vector. This relation shows that the peak value of a delta line current is equal to 1.732 times the peak value of coil current. The same relation also applies to the effective value of line and coil current.

In figure 5-12 (B) it can also be seen that line current lags the nearest coil current by 30°. It must also lag line voltage by 30°, because line voltage, coil voltage, and coil current are in phase in a balanced delta system. This is shown more clearly in figure 5-13.

Figure 5-13 (A) shows that coil voltage and line voltage are one and the same and are labeled E_C (E_L) for all three delta phases. These coil voltages are in phase with their coil currents I_{AB}, I_{BC}, and I_{CA}. As stated previously, line current lags coil current and voltage by 30° when the load is resistive and balanced. This relation for all three phases is shown in (A). That is, each of the line currents I_A, I_B, and I_C lag their respective nearest coil currents and voltages I_{AB}, I_{BC}, and I_{CA} by 30°.

Figure 5-13 (B) represents the same generator when a balanced inductive load is connected. Coil voltage and current are moved out of phases with each other by angle θ. When this happens, line current remains 30° out of phase with coil current, but is now $\theta + 30°$ out of phase with coil voltage.

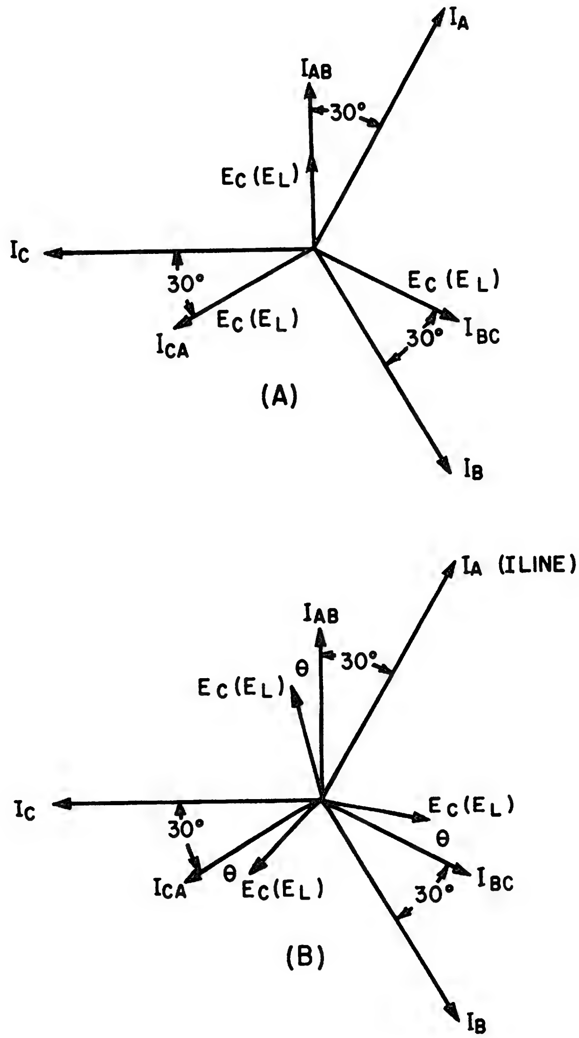

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Figure 5-13.—(A) Vectors for balanced nonreactive delta; (B) vectors for balanced reactive delta.

At this point, you should refer to figure 5-9 (B). Remember that this vector diagram represents a wye-connected generator supplying a balanced inductive load. Note that coil voltage E_{OA} and line voltage E_{AC} are considered fixed 30° apart, while coil current I_{OA} is varied by angle θ. However, in figure 5-13 (B) where the generator is connected delta, coil current I_{AB} and line current I_A are considered fixed 30° apart, while coil voltage E_C is varied by

$\angle\theta$. In the wye system, line voltage and current are 30° minus θ ° apart while in the delta system they are 30° plus θ ° apart, and the loads are identical in both cases. However, note that coil current lags coil voltage by θ in both systems. This is the reason for using coil phase angles for computing power instead of line phase angles, regardless of how the system is connected.

POWER IN DELTA SYSTEMS

Power in a delta system is computed in practically the same manner as in a wye system. Coil, or phase power, is $P_C = E_C \times I_C$, and total power is three times the phase power, or $P_T = 3 \times P_C$. If line current and voltage are used, then $P_T = 1.732 \times E_L \times I_L$. When the load is not reactive, total power and true power are the same. With a reactive load, however, where coil voltage and coil current are not in phase, then $E_C \times I_C$ represents phase volt-amperes (apparent power) only. True power per phase would be $E_C \times I_C \times \cos\theta$, and VARS per phase would be $E_C \times I_C \times \sin\theta$. Total true power in the system would be three times the phase true power, assuming each phase is the same, and total system VARS would be three times the phase VARS.

In an unbalanced system, total power is the sum of the power in all the phases, where each phase power is computed separately and then added to the others. As in the unbalanced wye system, the term system power factor is still practically meaningless when applied to an unbalanced delta system.

Figure 5-14 represents an a-c generator and a balanced inductive 3-phase load, connected first in wye, and then in delta. It can be seen that total apparent power, total true power, and total VARS are the same, respectively, in both systems when the following computations are applied to each.

The apparent power of one phase or coil is

$$AP_C = E_C \times I_C$$
$$= 100 \times 10$$
$$= 1{,}000 \text{ VA}$$

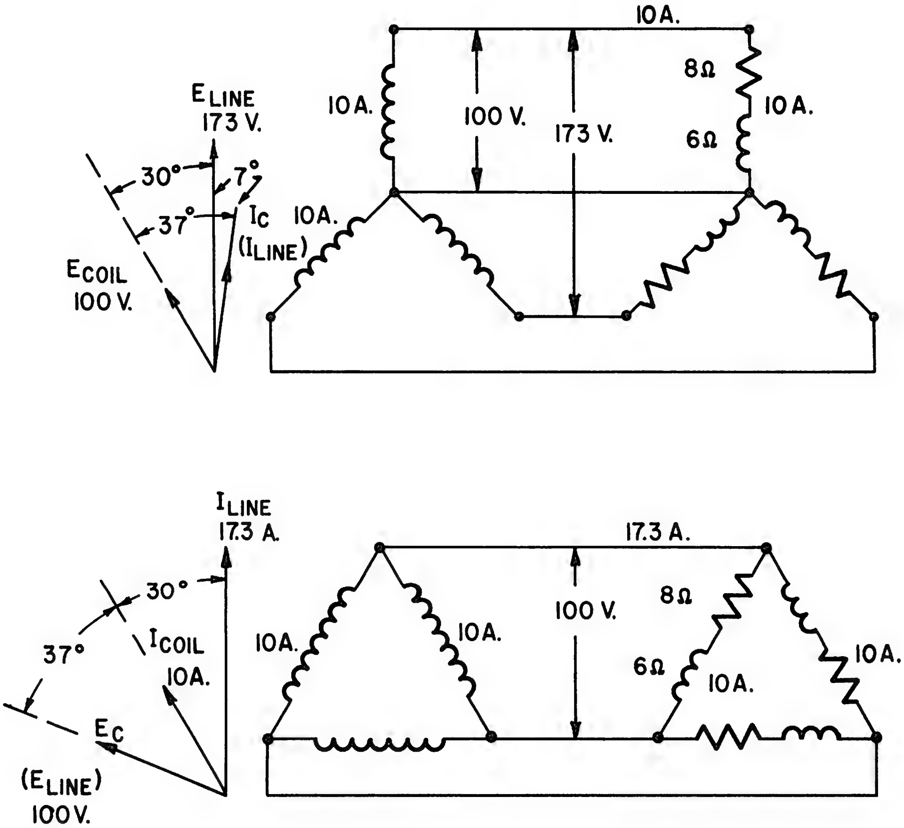

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Figure 5-14.—Phase relation of line current to line voltage in wye and delta systems.

To determine true power and VARS, angle θ must be determined, and is done as follows. The impedance of a load phase is $8 + J6\Omega$. Therefore the tangent of angle θ is J6/8:

$$\tan \theta = \frac{6}{8}$$
$$= 0.75$$
$$0.75 = \tan 37^\circ$$
$$\theta = 37^\circ$$

True power per phase is $AP_C \times \cos \theta$.

$$P_{TP} = AP_C \times \cos 37^\circ$$
$$= 1{,}000 \times 0.8$$
$$= 800 \text{ watts}$$

VARS per phase is $AP_C \times \sin \theta$.

$$VARS = AP_C \times \sin 37^\circ$$
$$= 1{,}000 \times 0.6$$
$$= 600 \text{ VARS}$$

Total true power is three times the true power per phase.

$$P_T = P_C \times 3$$
$$= 800 \times 3$$
$$= 2{,}400 \text{ watts.}$$

Total VARS is three times the VARS per phase.

$$VAR_T = VAR_C \times 3$$
$$= 600 \times 3$$
$$= 1{,}800 \text{ VARS}$$

Total apparent power is three times the phase apparent power.

$$AP_T = AP_C \times 3$$
$$= 1{,}000 \times 3$$
$$= 3{,}000 \text{ VA}$$

Total line power is the same as total phase power.

From the foregoing, it can be seen that coil, or phase voltages, currents, and phase angles are the same for both the wye and delta systems. The major differences, then, lie in their respective values of line voltages, currents, and phase angles. Where one has a higher voltage on a given line (173 v in the wye system, and 100 v in the delta), the other will have a higher current on its corresponding line (17.3 amp in delta system, and 10 amp in the wye). However, one factor compensates for the other so that line power is equal in both systems. This is shown as follows:

Line power for either system is:

$$P = 1.73 \times E_L \times I_L \text{VA}$$

Substituting wye line values, line power is

$$P = 1.73 \times 173 \text{ volts} \times 10 \text{ amp}$$
$$= 3{,}000 \text{ VA}$$

Substituting delta line values, line power is

$$P = 1.73 \times 100 \text{ volts} \times 17.3 \text{ amp}$$
$$= 3{,}000 \text{ VA}$$

Thus, in both systems, line power is 3,000 VA.

As already mentioned, another difference between the wye and delta system pertains to their respective line phase angles. This difference is shown in the vector diagrams in figure 5-14. To be correct, certain conditions must be met in both diagrams. Angle θ must be the same in either system with coil voltage leading coil current.

Also, wye line voltage must lag wye coil voltage by 30°, and delta line current must lag delta coil current by 30°. With θ equal to 37°, for the conditions shown, then the two vector diagrams are correct. It can be seen that under the load conditions shown, line current lags line voltage by 7° in the wye system, $(30^\circ + \theta = 30^\circ + (-37^\circ) = -7^\circ)$. It can also be seen that line current leads line voltage by 67° in the delta system under identical load conditions $(30^\circ - \theta = 30^\circ (-37^\circ) = 67^\circ)$.

ADMITTANCE, CONDUCTANCE, AND SUSCEPTANCE

SYMBOLOGY AND GENERAL FORMULAE

A-c problems may be solved by methods other than those given in chapter 4. One of these methods involves the use of admittance in various mathematical processes.

The admittance of an a-c circuit is similar to the conductance of a d-c circuit, in that both are reciprocal quantities. Where conductance (symbol G) is the reciprocal of resistance (1/R), admittance (symbol Y) is the reciprocal of impedance (1/Z). Admittance is the complex reciprocal of complex impedance. That is, if the complex

impedance of an a-c circuit is 2 - J4 Ω, then the admittance (always written in complex form) is the reciprocal of that impedance, or 1/(2 - J4). The unit of admittance, as for conductance, is the mho symbolized by ℧. The two rectangular members comprising admittance are conductance (G) and susceptance (B). Susceptance is the reciprocal of reactance ($1/X_C$ or $1/X_L$). The general form for representing admittance is thus written Y = G ± JB mhos. To demonstrate, the admittance will be determined for a circuit whose impedance is 2 + J5 Ω.

$$Y = \frac{1}{Z}$$

$$Y = \frac{1}{2 + J5}$$

$$= \frac{1}{2 + J5} \times \frac{2 - J5}{2 - J5}$$

$$= \frac{2 - J5}{29}$$

$$= 0.069 - J0.172 \ \mho$$

Note that Y is composed of 0.069 mho of conductance and -0.172 mho of susceptance. Note also that the sign of the J operator for an impedance is reversed when that impedance is converted to its admittance. It is important that this relation be fixed firmly in mind. That is, where the J operator for an inductive impedance is plus, the J operator for its admittance is minus. It follows that the same inverse relation applies for capacitive impedance.

Admittance, rather than impedance, may often be used to an advantage in certain types of problems. It will be used in this chapter for the solution of unbalanced polyphase power systems, and in the application of Millman's theorem.

SOLUTION OF CIRCUITS BY ADMITTANCE

You have solved a-c problems using the parameters I, E, and Z. You can also solve these problems by the use of I, E, and Y. To do so, however, you must first become familiar with the way in which Y is used in relation to I and E.

Consider the following algebraic relation of Z to Y:

$$\frac{Y}{1} = \frac{1}{Z} \text{ or } Y = \frac{1}{Z}$$

also

$$\frac{Z}{1} = \frac{1}{Y} \text{ or } Z = \frac{1}{Y}$$

Since Y is obviously the exact inverse of Z, then Y will always have the opposite effect in a mathematical formula that Z would have. That is, where Z is used as a multiplier, Y would be used as a divider, and vice versa. This inverted relation becomes apparent when you study the following columns in table 5-1. The left column consists of relations of I, E, and Z, with which you are familiar. The right-hand column gives the same relations, except that Z has been replaced by Y.

Table 5-1.—Relations of Y to Z.

$Z = \frac{1}{Y}$	$Y = \frac{1}{Z}$	(1)
$I = \frac{E}{Z}$	$I = E \times Y$	(2)
$E = I \times Z$	$E = \frac{I}{Y}$	(3)
$Z = \frac{E}{I}$	$Y = \frac{I}{E}$	(4)
$P = I^2 Z$	$P = \frac{I^2}{Y}$	(5)

In order to familiarize you with mathematical processes involving admittance, all of the five relations in the right-hand column of table 5-1 will be applied and their values solved for the circuit shown in figure 5-15, starting with (1). The total circuit admittance will be determined after solving the branch admittances Y_1 and Y_2 as follows:

$$Y_1 = \frac{1}{Z_1}$$

$$Y_1 = \frac{1}{6 - J8}$$

$$= \frac{1}{6 - J8} \times \frac{6 + J8}{6 + J8}$$

$$= \frac{6 + J8}{100}$$

$$= 0.06 + J0.08 \text{ mho (Answer)} \qquad (1)$$

$$Y_2 = \frac{1}{Z_2}$$

$$Y_2 = \frac{1}{4 + J6}$$

$$= \frac{1}{4 + J6} \times \frac{4 - J6}{4 - J6}$$

$$= \frac{4 - J6}{52}$$

$$= 0.077 - J0.115 \text{ mho (Answer)} \qquad (1)$$

To determine total circuit admittance, you need only to add all branch admittances. This is one of the advantages gained by the use of admittance. That is, the total admittance of a parallel circuit is determined as easily as the total resistance of a series circuit. This is true since both are determined by simply adding their respective values. Thus, total admittance (Y_T) in figure 5-15 is $Y_1 + Y_2$, added as follows: $(0.06 + J0.08) + (0.077 - J0.115)$, then $Y_T = 0.137 - J0.035$.

Total current I_T is determined by multiplying voltage E by total admittance Y_T.

$$I_T = E \times Y_T$$

$$I_T = (10 + J0) \times (0.137 - J0.035) =$$

$$\begin{array}{r} 10.000 + J0 \\ \underline{0.137 - J0.035} \\ 1.37 + J0 \\ - J0.35 - J^2 0 \\ \hline 1.37 - J0.35 \text{ amp (Answer)} \end{array} \qquad (2)$$

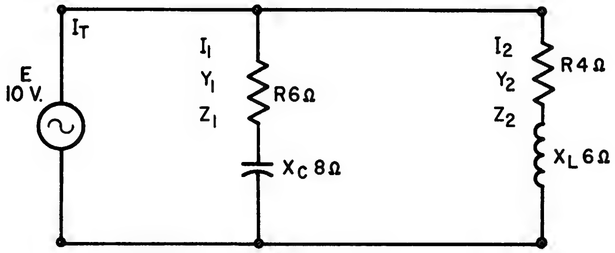

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Figure 5-15.—Circuit for computing total admittance.

Branch currents I_1 and I_2 could also be determined by multiplying the voltage by branch admittances Y_1 and Y_2.

If E is not known, but I_T and Y_T are given, E may be determined as follows:

$$E = \frac{I}{Y}$$

$$= \frac{1.37 - J0.35}{0.137 - J0.035}$$

$$= \frac{1.37 - J0.35}{0.137 - J0.035} \times \frac{0.137 + J0.035}{0.137 + J0.035}$$

$$= \frac{0.20 + J0}{0.020}$$

$$= 10 + J0 \text{ volts (Answer)} \qquad (3)$$

Where I_T and E are known, and Y_T must be determined, then:

$$Y_T = \frac{I_T}{E}$$

$$= \frac{1.37 - J0.35}{10 + J0}$$

$$= \frac{1.37 - J0.35}{10 + J0} \times \frac{10 - J0}{10 - J0}$$

$$= \frac{13.7 - J3.5}{100}$$

$$= 0.137 - J0.035 \text{ mho (Answer)} \qquad (4)$$

Power can be determined when current I_T and admittance Y_T are known.

$$P = \frac{I_T^2}{Y_T}$$

$$= \frac{(1.37 - J0.35)^2}{0.137 - J0.035}$$

$$= \frac{1.76 - J0.96}{0.137 - J0.035}$$

$$= \frac{1.76 - J0.96}{0.137 - J0.035} \times \frac{0.137 + J0.035}{0.137 + J0.035}$$

$$= \frac{0.275 - J0.0699}{0.020}$$

$$= 13.7 - J3.49 \text{VA (Answer)} \qquad (5)$$

MILLMAN'S THEOREM

This theorem pertains to a special method of analysis for 2-node networks. A 2-node network is one consisting of two or more branches connected in parallel. The "nodes" of such a network are those two points where all branch ends terminate. For instance, the standard aircraft d-c power system is a typical two-node network. One node is the d-c power bus, where all d-c branches, including generators and batteries, terminate at a common high-potential point. The other node is the airframe, where all branches terminate to ground, or a common low potential point.

Millman's theorem enables you to determine the node-to-node voltage of a parallel network when more than one source of potential, each different from the other, is supplying power. Such a condition exists, for instance, when a 28-volt generator and a 24-volt battery are connected to the same bus. Depending on the size of the load connected, bus voltage (node-to-node voltage) will probably be between 28 and 24 volts. However, if the load were heavy enough, bus voltage could be less than 24 volts. The problem of computing the current supplied by each power source under various load conditions would be simplified if the bus voltage could be determined for each condition. This is exactly what can be done by use of the Millman method where the bus and ground are treated as the two nodes of a parallel network.

Figure 5-16 shows two unequal current sources connected in parallel between the common nodes O and N. E_1 represents a generator with an emf of 28 volts, and whose internal resistance is R1. The conductance of R1 is G_1, and e_1 represents the generator's internal voltage drop when it is supplying current. E_2 is a battery with an emf of 24 volts, and whose internal resistance is R2. The conductance of R2 is G_2, and e_2 represents the battery's internal voltage drop when it is either supplying current or is being charged. The system load is R3.

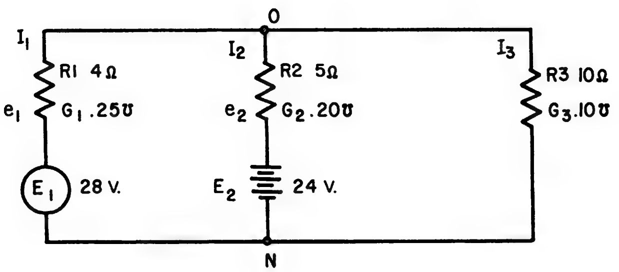

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Figure 5-16.—A 2-node network with unequal current sources.

The problem is to determine the current supplied by the generator (I_1) and battery (I_2) when the load is as shown. This can be done when the node-to-node voltage E_{ON} is known. (E_{ON} is merely the terminal voltage of the current sources under load.) Millman's theorem states that the voltage across a 2-node network is equal to the sum of the currents in all the potential sources, divided by the sum of all branch conductances. The source currents are expressed in terms of source emf and the conductance of the source's internal resistance, (I = E x G). The general mathematical form of Millman's theorem is

$$E_{ON} = \frac{\text{all source currents}}{\text{all branch conductances}}$$

When this formula is applied to the circuit shown in figure 5-16, it is as follows:

$$E_{ON} = \frac{I_1 + I_2}{G_1 + G_2 + G_3}$$

$$E_{ON} = \frac{E_1G_1 + E_2G_2}{G_1 + G_2 + G_3}$$

$$= \frac{(28 \times 0.25) + (24 \times 0.20)}{0.25 + 0.20 + 0.10}$$

$$= \frac{7 + 4.8}{0.55}$$

$$= 21.45 \text{ volts}$$

With E_{ON} known, the load current I_3 can be readily determined.

$$I = E \times G$$

$$I_3 = E_{ON} \times G_3$$

$$= 21.45 \times 0.1$$

$$= 2.145 \text{ amp}$$

The internal voltage drop of the generator (e_1) must be the difference between its generated emf and its terminal voltage.

$$e_1 = E_1 - E_{ON}$$

$$= 28 - 21.45$$

$$= 6.55 \text{ volts}$$

The internal voltage drop of the battery is

$$e_2 = E_2 - E_{ON}$$

$$= 24 - 21.45$$

$$= 2.55 \text{ volts}$$

Generator current can now be determined.

$$I = E \times G$$

$$I_1 = e_1 \times G_1$$

$$= 6.55 \times 0.25$$

$$= 1.635 \text{ amp}$$

Battery current can also be determined.

$$I_2 = e_2 \times G_2$$

$$= 2.55 \times 0.20$$

$$= 0.510 \text{ amp}$$

As a final check, I_3 should equal the sum of I_2 and I_1.

$$I_1 + I_2 = I_3$$

$$1.635 + 0.510 = 2.145$$

$$2.145 = 2.145 \text{ (check)}.$$

It can readily be seen that the use of the Millman formula is a more convenient method for solving this type of problem than the application of Kirchoff's laws, or the various mesh methods. The Millman method does not require the use of lengthy simultaneous linear equations. In addition to its usefulness as a method of solving d-c systems, it is also extremely useful in the analysis and solution of polyphase a-c systems. The major difference in the two applications is that when the Millman theorem is applied to a-c systems, admittances, rather than simple conductances, are used in the formula.

As previously stated, the Millman method enables you to resolve a number of unequal potentials into a single node-to-node value. This is the key to its usefulness in solving polyphase a-c problems. The coil emf's in a 3-phase system are always different from each other if their instantaneous values are considered. Therefore, they may be considered as three instantaneously unequal current sources, and their net result may be resolved into a single instantaneous value when the three emf's are connected between two nodes. However, even instantaneous values will establish phase relations which are constant.

Figure 5-17 represents a balanced wye-connected system with no neutral conductor. Part (B) shows how each instantaneous coil emf is identified by its rectangular coordinates. The instantaneous magnitude and direction of each coil emf is also indicated by the arrows in part (A). The three coils are supplying power between the two nodes O and O', so their instantaneous resultant potential E_{OO}' may be determined by the use of Millman's theorem. The three loads are equal, so their admittances are equal. Since the system is balanced, there should be no difference in potential between O and O'. That is, $E_{OO}' = 0$. This will be proven by the application of Millman's theorem. The load admittances must be solved first, since they appear in the theorem formula.

$$Y_A = \frac{1}{Z_A}$$

$$= \frac{1}{10 + J0}$$

$$= \frac{1}{10 + J0} \times \frac{10 - J0}{10 - J0}$$

$$= \frac{10 - J0}{100}$$

$$= 0.1 - J0$$

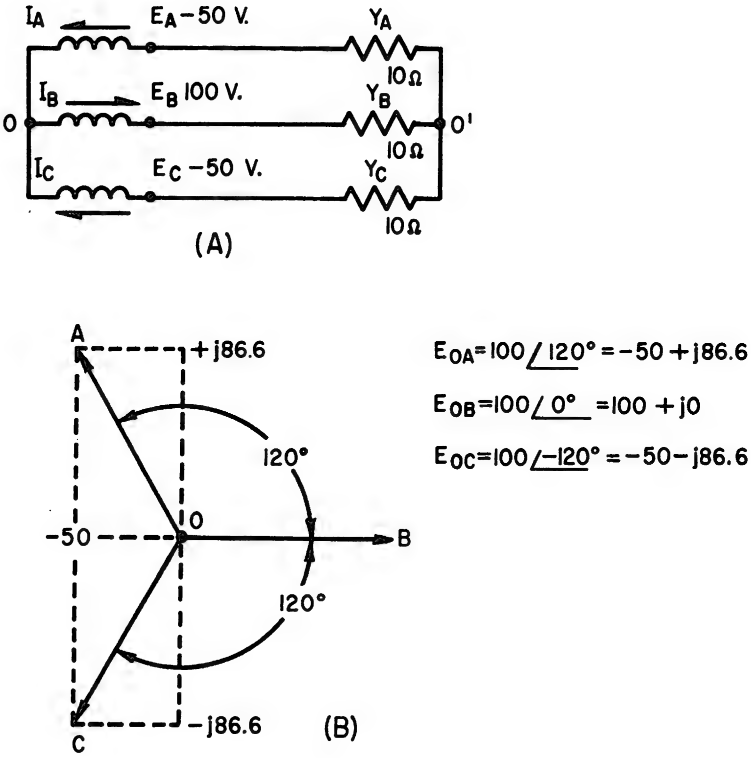

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Figure 5-17.—Instantaneous representations of 3-phase voltages.

All the load admittances are equal, so 0.1 - J0 ℧ is the admittance for any of the three branches. Solving for E_{OO}' can now be carried out.

$$E_{OO}' = \frac{I_A + I_B + I_C}{Y_A + Y_B + Y_C}$$

$$= \frac{E_AY_A + E_BY_B + E_CY_C}{Y_A + Y_B + Y_C}$$

$$= \frac{(-50+J86.6)(0.1-J0)+(100+J0)(0.1-J0) +(-50-J86.6)(0.1-J0)}{(0.1-J0)+(0.1-J0)+(0.1-J0)}$$

$$= \frac{(-5+J8.66)+(10+J0)+(-5-J8.66)}{0.3-J0}$$

$$= \frac{0}{0.3-J0}$$

$$E_{OO}' = 0$$

This proves what was already stated -- that E_{OO}' is zero for a balanced system. However, you should study carefully the manner in which the system quantities were operated with one another. In this way you will be able to solve unbalanced systems more readily.

UNBALANCED POLYPHASE SYSTEMS

Up to this point, only balanced polyphase systems have been discussed. For purposes of explanation, it was assumed that ideal conditions existed, where all phase voltages, currents, and power rates were equal. Moreover, it was assumed that the 3-phase voltages were exactly 120° apart in their time-phase relations to each other. In practice, however, such ideal conditions rarely exist.

It is practically impossible to connect a number of separate loads to a 3-phase generator in such a way that the demand on each phase is exactly equal to the demand on any other phase. This is especially true when the types of loads

are not identical (motors, lighting, transformers, etc.). In addition to unequal wattage demands, each load component will most likely have a different reactive characteristic. The resulting unequal phase currents will produce an unbalanced condition in the system's line voltages. They will either be unequal in magnitude or no longer 120° apart. In many cases both conditions will exist. The amount of imbalance or phase displacement depends on the differences of the loads and the loading characteristics of the generator. Obviously, this imbalance must be kept at a minimum, and should be of prime consideration when loads are either removed from or connected in a polyphase power system. You should be familiar with the causes and effects and the methods of correcting for unbalanced systems.

CAUSES OF IMBALANCE

In 3-phase systems the causes of imbalance are: (1) Single-phase loads of unequal volt-ampere demand; (2) loads of equal volt-ampere demand, but with unequal reactive characteristics (power factor); and (3) fault conditions.

EFFECTS OF UNBALANCED LOADING

The effects of unbalanced loading depend on the characteristics of the generator, the impedance of the line conductors, and the design of the generator's voltage regulator circuit. Some regulators sense the voltage of one phase, while others sense the average of all three phases. In general, excessive current in one phase will cause a rise in voltage in at least one of the other phases. At the same time, the phase voltages will no longer be at the desired 120° from each other.

Another effect of unbalanced loading is that the total capacity of the generator is reduced. For example, consider a 6,000 VA generator with a rating of 2,000 VA for each phase. Assume that a single-phase load of 500 VA has been placed on one phase. The maximum additional 3-phase load the generator can now carry is 4,500 VA, with 1,500 VA being placed on each phase. At this time, the preloaded phase is carrying 2,000 VA, its rated capacity, while two phases are carrying only 1,500 VA each. No additional 3-phase load may be added without danger of overloading the phase carrying 2,000 VA. Thus, by connecting an unbalanced load, the total capacity of the generator has been reduced from 6,000 VA to 5,000 VA (2,000 + 1,500 + 1,500 = 5,000).

The performance specifications a power source (aircraft a-c generator and voltage regulator) must meet to be acceptable to the Navy are given in Military Specification MIL-STD-704. The following is taken from that specification.

UNBALANCED LOADS

The effects of single-phase and unbalanced 3-phase loads on the voltage balance of a 3-phase generator must be determined as follows, at both maximum and minimum rated speeds:

1. Starting with the generator carrying no load, a nonreactive (unity power factor) load shall be placed on one phase. This load shall require first one-third and then two-thirds of the rated output current from that phase.
2. Starting with the generator carrying a 3-phase unity power factor load demanding one-third of the rated output from each phase, an additional unity power factor load will be placed on one phase. The additional load will demand first one-third and then two-thirds of the rated output of that phase, so that finally the one phase is supplying full rated output current.
3. Starting with the generator carrying a 3-phase unity power factor load demanding two-thirds of the rated output from each phase, an additional unity power factor load will be placed on one phase. The additional load will demand one-third of the rated output of that phase, so that the one phase is supplying full rated output current.

Under the conditions just described, the maximum voltage imbalance must not exceed 4 percent. The percentage of imbalance is computed as follows:

$$\text{Percent imbalance} = \frac{100 \times \text{maximum deviation from average}}{\text{average}}$$

The average voltage is the arithmetical sum of the three unequal voltages divided by three. Maximum deviation is the difference between the voltage of the phase that is farthest from average, and the average.

In addition to the limitation of 4 percent placed on the voltage magnitude imbalance, a limitation is also placed on the time phase displacement between phases. The phase displacement must be 120°, ± 1.5°. That is, no two

phases may be nearer than 118.5° to each other, nor more than 121.5° apart.

SOLUTION OF UNBALANCED SYSTEMS

SOLUTION OF UNBALANCED DELTA SYSTEMS

The solution of an unbalanced delta system is greatly facilitated by the fact that there are three separate current loops. Each loop may be treated as a simple single-phase circuit. In figure 5-18 (A), the three loops are BAA'B'B, CBB'C'C and ACC'A'A. In each loop there is one phase coil emf and one phase load impedance. Consequently, each instantaneous loop current can be determined by use of its instantaneous emf and load impedance. This will yield instantaneous phase, or coil, current only. The line currents I_A, I_B, and I_C will be different from the phase currents because each line is part of two loops, Consequently, any line current is a combination of two loop currents.

In a balanced condition, it was shown that either peak or average delta line current was equal to either peak or average phase current times $\sqrt{3}$, or 1.73. It was also shown that the three line currents were 120° apart. In an unbalanced condition, however, these relations are generally no longer true. However, even when the delta system is unbalanced, it can still be stated that any line current is equal to the difference of the two phase currents to which the line is connected. For this reason the phase currents must be determined prior to determining the line currents. This will be done for the system in figure 5-18 (A).

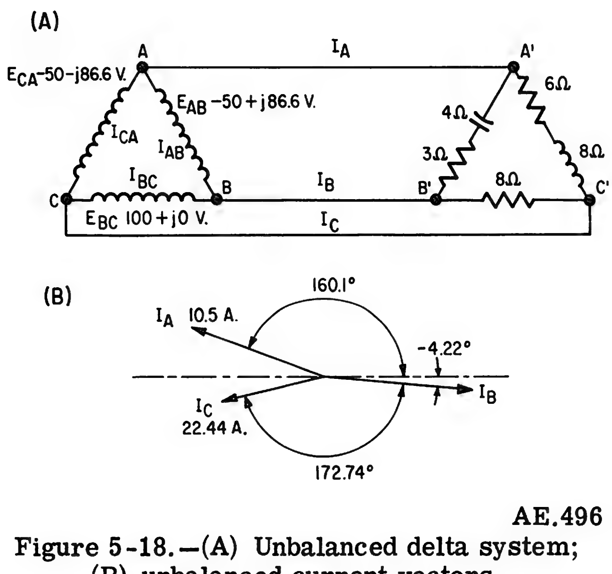

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Figure 5-18.—(A) Unbalanced delta system; (B) unbalanced current vectors.

$$E_{AB} = -50 + J86.6 \text{ V}$$

$$Z_{A'B'} = 3 - J4\,\Omega$$

$$I_{AB} = \frac{E_{AB}}{Z_{A'B'}}$$

$$= \frac{-50 + J86.6}{3 - J4}$$

$$= \frac{-50 + J86.6}{3 - J4} \times \frac{3 + J4}{3 + J4}$$

$$= \frac{-496.4 + J59.8}{25}$$

$$= -19.8 + J2.39 \text{ amp}$$

$$E_{BC} = 100 + J0 \text{ V}$$

$$Z_{B'C'} = 8 + J0\,\Omega$$

$$I_{BC} = \frac{E_{BC}}{Z_{B'C'}}$$

$$= \frac{100 + J0}{8 + J0}$$

$$= \frac{100 + J0}{8 + J0} \times \frac{8 - J0}{8 - J0}$$

$$= \frac{800 + J0}{64}$$

$$= 12.5 + J0 \text{ amp}$$

$$E_{CA} = -50 - J86.6 \text{ V}$$

$$Z_{C'A'} = 6 + J8\,\Omega$$

$$I_{CA} = \frac{E_{CA}}{Z_{C'A'}}$$

$$= \frac{-50 - J86.6}{6 + J8}$$

$$= \frac{-50 - J86.6}{6 + J8} \times \frac{6 - J8}{6 - J8}$$

$$= \frac{-992 - J119}{100}$$

$$= -9.92 - J1.19 \text{ amp}$$

With the phase currents known, the line currents can now be determined.

$$I_A = I_{AB} - I_{CA}$$

$$= (-19.8 + J2.39) - (-9.92 - J1.19)$$

$$= -19.8 + J2.39 + 9.92 + J1.19$$

$$= -9.88 + J3.58 \text{ amp}$$

$$I_B = I_{BC} - I_{AB}$$

$$= (12.5 + J0) - (-19.8 + J2.39)$$

$$= 12.5 + J0 + 19.8 - J2.39$$

$$= 32.3 - J2.39 \text{ amp}$$

$$I_C = I_{CA} - I_{BC}$$

$$= (-9.92 - J1.19) - (12.5 + J0)$$

$$= -9.92 - J1.19 - 12.5 - J0$$

$$= -22.42 - J1.19 \text{ amp}$$

If the solutions for line currents are correct, the sum of the line currents will be zero.

$$I_A + I_B + I_C = 0$$

$$
\begin{array}{l}
-9.88 + J3.58 \\
32.30 - J2.39 \\
-22.42 - J1.19 \\
\hline
\quad 0 + J0 \qquad \text{(Check).}
\end{array}
$$

Further clarification of unbalanced delta current relations will be obtained by converting the line currents from rectangular to polar form and constructing a vector diagram. The polar form of the line currents are as follows:

$$I_A = -9.88 + J3.58 = 10.5 \angle 160.1^\circ$$

$$I_B = 32.3 - J2.39 = 32.32 \angle -4.22^\circ$$

$$I_C = -22.42 - J1.19 = 22.44 \angle -176.96^\circ$$

When these three current vectors are used to construct a diagram, the result is as shown in figure 5-18 (B). In this case, the vectors represent instantaneous current magnitudes by their length. Since these vectors would have been 120° apart had the system been balanced, it can be seen that the degree of imbalance in figure 5-18 (B) is quite severe in both magnitude and phase displacement. The phase displacement between I_A and I_B is 160.1° + 4.22° = 164.32°. Between I_B and I_C the displacement is 176.96° - 4.22° = 172.74°. Between I_C and I_A it is (180° - 160.1°) + (180° - 176.96°) = 19.9° + 3.04° = 22.94°.

The power in each phase is the phase voltage times the phase current. Remember that the conjugate of the voltage must be used.

$$P_{AB} = E_{AB} \times I_{AB} \text{ VA}$$

$$= (-50 + J86.6) \times (-19.8 + J2.39)$$

$$= (-50 - J86.6) \times (-19.8 + J2.39)$$

$$= 990 + J1,593 - J^2 207$$

$$= 1,197 + J1,593 \text{ VA}$$

$$P_{BC} = E_{BC} \times I_{BC}$$

$$= (100 + J0) \times (12.5 + J0)$$

$$= (100 - J0) \times (12.5 + J0)$$

$$= 1,250 + J0 + J^2 0$$

$$= 1,250 + J0 \text{ watts}$$

$$P_{CA} = E_{CA} \times I_{CA}$$

$$= (-50 - J86.6) \times (-9.92 - J1.19)$$

$$= (-50 + J86.6) \times (-9.92 - J1.19)$$

$$= +496 - J799.5 - J^2 103$$

$$= +599 - J799.5 \text{ VA}$$

With each phase power known, total power can be determined. Total power in an unbalanced system is the sum of the phase powers. The total instantaneous power for the system in figure 5-18 is:

$$P_T = P_{AB} + P_{BC} + P_{CA}$$

$$= (1,197 + J1,593) + (1,250 + J0) + (+599 - J799.5)$$

$$= 3046 + J793.5 \text{ VA}$$

SOLUTION OF UNBALANCED WYE SYSTEMS

In general, it is important that the AE be more familiar with the analysis and solution of unbalanced wye systems than unbalanced delta systems. This is true because military specifications require that the a-c power systems in naval aircraft be connected in wye. For this reason the solution of wye systems is given somewhat more complete coverage than the solution of delta systems. This coverage is given in the form of a series of exemplary problems.

Problem 1. For the unbalanced 3-wire system shown in figure 5-19 (A), solve for the line currents and the voltage across each load phase, with the instantaneous generated emf's as shown.

NOTE: In a 4-wire system, the neutral of the load is connected to the neutral of the source, so that the voltage and current of each phase loop may be treated and solved separately. In a 3-wire system, the neutrals are not connected, and are allowed to shift away from each other in what is called a "floating neutral." Under these conditions, it is necessary to determine the actual voltage between the neutrals before attempting to solve for the phase currents. This must be done, because the neutral-to-neutral voltage may aid one phase emf while bucking another. Since the neutrals may be treated as the two nodes mentioned in Millman's theorem, this theorem may be used to solve the problem. The voltage between the nodes O and N in figure 5-19 (A) is

$$E_{ON} = \frac{E_AY_1 + E_BY_2 + E_CY_3}{Y_1 + Y_2 + Y_3}$$

Impedances:	Admittances:
$R1 = 12.5 + J0\ \Omega$	$Y_1 = 0.08\ ℧$
$R2 = 8.0 + J0\Omega$	$Y_2 = 0.125℧$
$R3 = 5.0 + J0\Omega$	$Y_3 = 0.200\ ℧$

Summation of Y's = 0.405 ℧

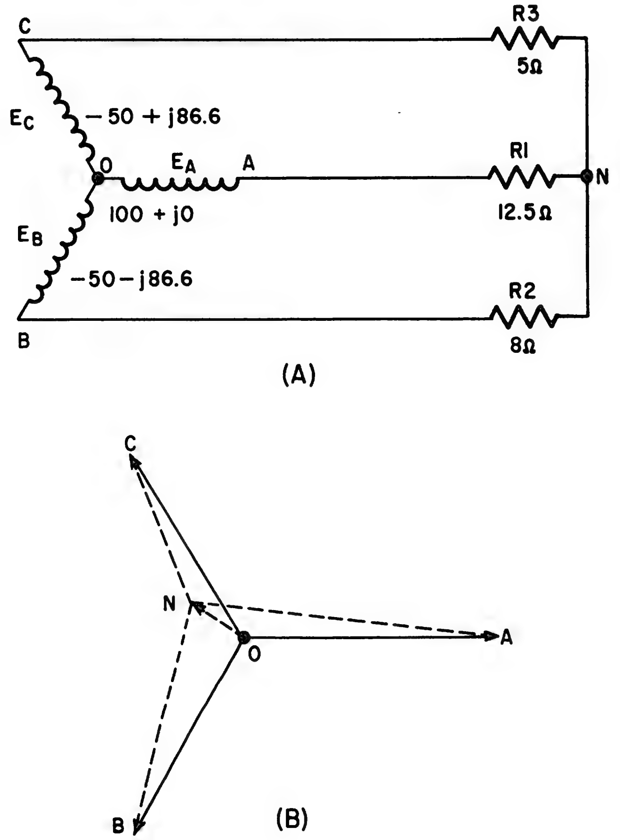

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Figure 5-19.—(A) Unbalanced 3-wire wye; (B) difference of generated emf's and load voltages.

Due to the unbalanced load, it can be seen that the voltage across each load phase is not equal to the fundamental generated emf of the generator phase to which it is connected. Figure 5-19 (B) represents the phase load voltage vectors E_{NA}, E_{NB}, and E_{NC} superimposed on the fundamental generated voltages E_{OA}, E_{OB}, and E_{OC}. The magnitude and direction of E_{ON} can thus be depicted as a line drawn from the generator neutral O to the load neutral N. It can be seen how E_{ON} acts to increase E_{OA} to produce E_{NA}, to increase E_{OB} to E_{NB}, and to decrease E_{OC} to E_{NC}.

$$E_AY_1 = (100 + J0) \times 0.08 = 8.0 + J0$$

$$E_BY_2 = (-50 - J86.6) \times 0.125 = -6.25 - J10.83$$

$$E_CY_3 = (-50 + J86.6) \times 0.20 = -10.0 + J17.32$$

Summation of EY's = -8.25 + J6.49

$$E_{ON} = \frac{E_AY_1 + E_BY_2 + E_CY_3}{Y_1 + Y_2 + Y_3} = \frac{-8.25 + J6.49}{0.405}$$

$$= -20.37 + J16.03$$

Solution for line currents:

$I_A = (E_A - E_{ON})\, Y_1$

$= [(100 + J0)-(-20.37 + J16.03)] \times 0.08$

$= (100 + 20.37 - J16.03) \times 0.08$

$= (120.37 - J16.03) \times 0.08$

$= 9.63 - J1.28 = 9.72 \underline{/-7.6^\circ}$ amp

$I_B = (E_B - E_{ON})\, Y_2$

$= [(-50 - J86.6)-(-20.37 + J16.03)] \times 0.125$

$= (-50 - J86.6 + 20.37 - J16.03) \times 0.125$

$= (-29.63 - J102.63) \times 0.125$

$= -3.70 - J12.83 = 13.3 \underline{/-163.9^\circ}$ amp

$I_C = (E_C - E_{ON})\, Y_3$

$= [(-50 + J86.6)-(-20.37 + J16.03)] \times 0.2$

$= (-50 + J86.6 + 20.37 - J16.03) \times 0.2$

$= (-29.63 + J70.57) \times 0.2$

$= -5.93 + J14.11 = 15.3 \underline{/157.2^\circ}$ amp

NOTE: As there is no neutral conductor for current, the sum of the line currents must equal zero.

$I_A = 9.63 - J1.28$

$I_B = -3.70 - J12.83$

$\underline{I_C = -5.93 + J14.11}$

Summation of I's = 0.0 + J0.0.
The phase voltages of the load are:

$E_{NA} = I_A \times R_1 = 9.72 \times 12.5 = 121.5$ volts

$E_{NB} = I_B \times R_2 = 13.3 \times 8 = 106.4$ volts

$E_{NC} = I_C \times R_3 = 15.3 \times 5 = 76.5$ volts

Problem 2. Figure 5-20 represents a 4-wire unbalanced wye system, with a voltage regulator designed to maintain phase A terminal voltage at 120 volts. In addition, the generator windings have an inductive reactance of 3 Ω in each winding. The system is simplified for solution as shown in figure 5-20 (B).

Phase A is used as a reference because the voltage regulator will always maintain its terminal voltage at 120 volts.

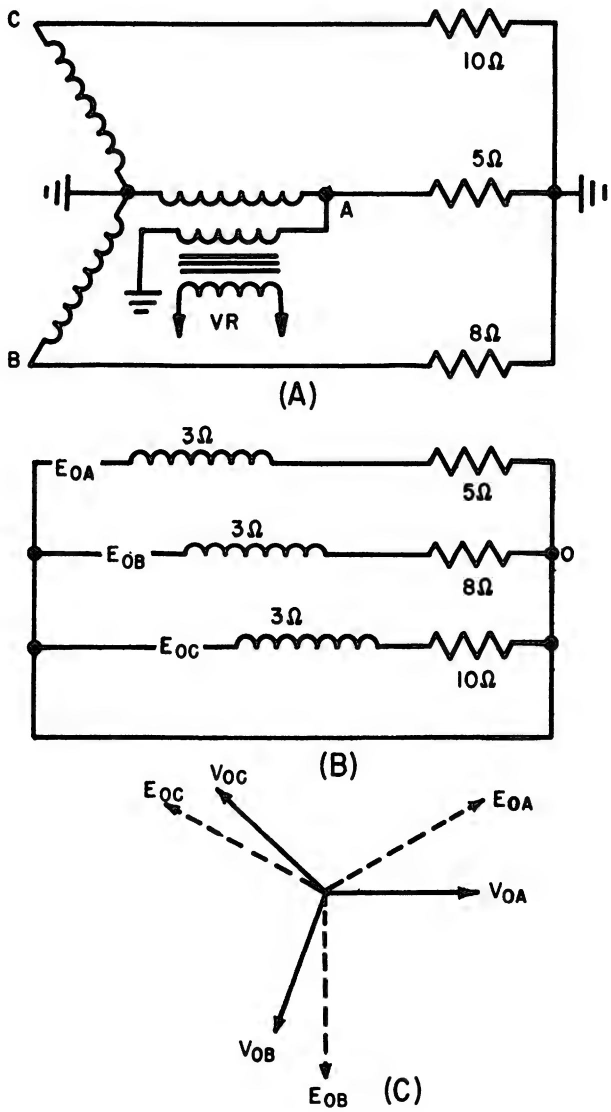

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Figure 5-20.—(A) Four-wire unbalanced wye; (B) simplified system; (C) difference of fundamental and terminal voltages.

$$I_A = \frac{V_{OA}}{Z_A} = \frac{120 + J0}{5} = 24 + J0 \text{ amp}$$

IX of generator = (24 + J0) x J3 = 0 + J72

(NOTE: X denotes the reactance of single-phase winding of the generator.)

$$E_{OA} = V_{OA} + IX = (120 + J0) + (0 + J72)$$
$$= 120 + J72$$
$$E_{OA} = 140 \angle 31^\circ$$

E_{OB} and E_{OC} may be determined since the excitation field is common to all three phases and the phase windings are displaced by 120 electrical degrees.

$$E_{OB} = 140 \angle 31^\circ \times 1 \angle -120^\circ = 140 \angle -89^\circ$$

$$E_{OC} = 140 \angle 31^\circ \times 1 \angle 120^\circ = 140 \angle 151^\circ$$

It is now possible to solve for current and terminal voltages of phases B and C.

$$I_B = \frac{E_{OB}}{Z_B} = \frac{140 \angle -89^\circ}{8 + J3} = \frac{140 \angle -89^\circ}{8.54 \angle 20.6^\circ}$$
$$= 16.4 \angle -109.6^\circ$$
$$= -5.5 - J15.4 \text{ amp}$$
$$V_{OB} = 8 \times 16.4 \angle -109.6^\circ = 131 \angle -109.6^\circ$$

$$I_C = \frac{E_{OC}}{Z_C} = \frac{140 \angle 151^\circ}{10 + J3} = \frac{140 \angle 151^\circ}{10.4 \angle 16.7^\circ}$$
$$= 13.4 \angle 134.3^\circ$$
$$= -9.35 + J9.6 \text{ amp}$$
$$V_{OC} = 10 \times 13.4 \angle 134.3^\circ = 134 \angle 134.3^\circ$$

The current carried by the neutral (ground) wire will be equal to the vector sum of the separate line currents.

$$I_A = 24.0 + J0.0$$

$$I_B = -5.5 - J15.4$$

$$I_C = -9.35 + J9.6$$

$$I_N = 9.15 - J5.8 = 10.8 \angle -32.4^\circ$$

This current is a result of the unbalanced loads; and whenever there is a low impedance path provided for it, the percentage of voltage imbalance will be reduced.

Figure 5-20 (C) shows that the generator neutral and load neutral are the same, because they are connected directly by the fourth conductor, or ground. It shows also how the fundamental generated voltage in each phase is affected by its load and winding reactance so that the final and actual terminal voltage for each phase is quite different from the fundamental emf.

The percent of phase terminal voltage unbalance may be found by:

$$\text{Percent imbalance} = \frac{100 \times \text{maximum deviation from average}}{\text{average}}$$

where the average voltage is:

$$\frac{120 + 134 + 131}{3} = 128 \text{ volts}$$

Maximum deviation from average voltage is 128 - 120 = 8 volts.
Imbalance is

$$\frac{100 \times 8}{128} = 6.25 \text{ percent.}$$

The above example illustrates the disadvantage of having the voltage control on only one phase in that it will allow excessively high voltages on the unregulated phases when the regulated phase is heavily loaded. On the other hand, if the regulated phase is lightly loaded, the unregulated phase voltages will be below normal. Single-phase sensing does have the advantage of providing close voltage regulation on one phase of the system in order to accommodate voltage-sensitive loads. Unbalanced loading, however, generally results in greater voltage imbalance with single-phase sensing than when the average voltage of the three phases is regulated.

Problem 3. This problem involves the same system used in problem 2, except that a 3-phase sensing voltage regulator and a load contactor are added. Figure 5-21 (A) will be used as reference for this problem.

Before the load is connected, the terminal voltage is the no-load voltage of 120 volts per phase. When the load contactor is closed, there will be a transient flow of current equal to the no-load voltage divided by the total impedance of each phase.

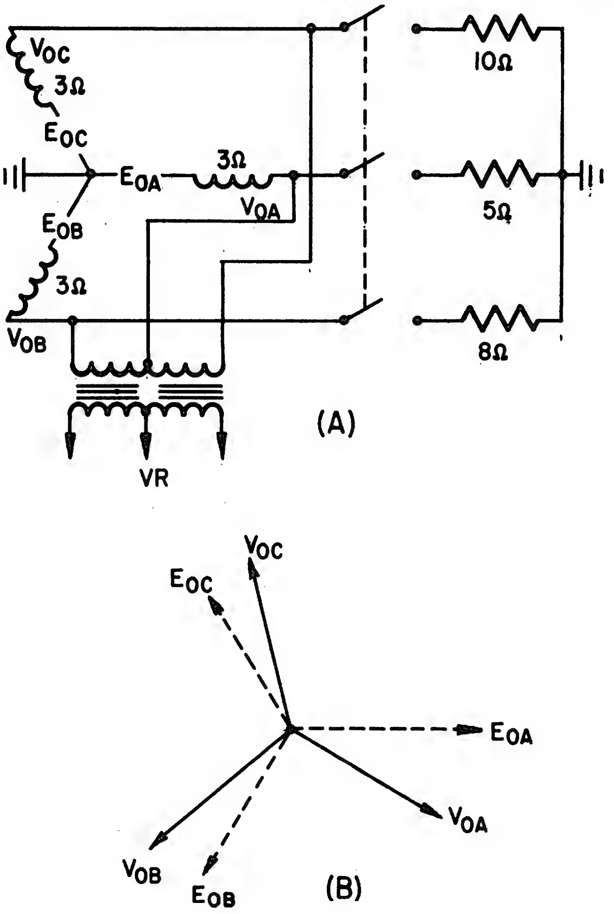

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Figure 5-21.—(A) Four-wire unbalanced wye, using 3-phase sensing voltage control; (B) difference of fundamental emf and terminal voltage.

$$I_A = \frac{E_{OA}}{Z_A} = \frac{120 \angle 0^\circ}{5 + J3} = \frac{120 \angle 0^\circ}{5.84 \angle 31^\circ}$$

$$= 20.6 \angle -31^\circ$$

$$I_B = \frac{E_{OB}}{Z_B} = \frac{120 \angle -120^\circ}{8 + J3} = \frac{120 \angle -120^\circ}{8.54 \angle 20.6^\circ}$$

$$= 14.1 \angle -140.6^\circ$$

$$I_C = \frac{E_{OC}}{Z_C} = \frac{120 \angle 120^\circ}{10 + J3} = \frac{120 \angle 120^\circ}{10.4 \angle 16.7^\circ}$$

$$= 11.5 \angle 103.3^\circ$$

The terminal voltages will be equal to line current times load impedance.

$$V_{OA} = 5 \times 20.6 \angle -31^\circ = 103 \angle -31^\circ$$

$$V_{OB} = 8 \times 14.1 \angle -140.6^\circ = 112 \angle -140.6^\circ$$

$$V_{OC} = 10 \times 11.5 \angle 103.3^\circ = 115 \angle 103.3^\circ$$

The average of these three voltages is sensed by the voltage regulator.

$$E_{AV} = \frac{103 + 112 + 115}{3} = 110 \text{ volts}$$

As the regulator is adjusted to maintain an average voltage of 120 volts, it will increase the field excitation in order to bring the average terminal voltage up to 120 volts. This may be approximated for instructional purposes only as an additional 10-volt increase on each phase voltage (true solution involves more complicated mathematics). The three terminal voltages will now become

$$V_{OA} = 113 \angle -31^\circ$$

$$V_{OB} = 122 \angle -140.6^\circ$$

$$V_{OC} = 125 \angle 103.3^\circ$$

The percentage of imbalance will be approximately:

$$\frac{100 \times (120 - 113)}{120} = \frac{700}{120} = 5.84 \text{ percent.}$$

The current in the ground neutral will be the vector sum of the phase currents.

$$I_A = 20.6 \angle -31^\circ = 17.6 - J10.6$$

$$I_B = 14.1 \angle -140.6^\circ = -10.9 - J8.95$$

$$I_C = 11.5 \angle 103.3^\circ - 2.64 + J11.2$$

$$I_N = 9.29 \angle -64^\circ = 4.06 - J8.35 \text{ amp}$$

Figure 5-21 (B) shows the difference between the fundamental emf and terminal voltage of each phase. Remember that this diagram represents a system whose voltage control is based on the sensing of the average of the 3-phase voltages. Figure 5-20 (B) represented a system

whose voltage control was based on the voltage of only one phase. Note the significant difference between the two.

The preceding problem illustrates a principle of voltage control based upon the average of the three circuit voltages. On unbalanced loading, the average voltage will be maintained at the adjusted value even though none of the single-phase voltages are equal to the adjusted value. Note also that the amount of imbalance is somewhat reduced.

Problem 4. Considering the same system, determine what would occur should the neutral (ground) wire become open under an unbalanced load condition.

NOTE: In a 3-wire wye system, the solution is simplified by use of the Millman theorem.

With the power contactor open, the terminal voltage will equal the no-load voltage and will be maintained at a value of 120 volts per phase by the regulator.

$$V_{OA} = E_{OA} = 120\,\underline{/0^\circ} = 120 + J0.0$$

$$V_{OB} = E_{OB} = 120\,\underline{/-120^\circ} = -60 - J104.0$$

$$V_{OC} = E_{OC} = 120\,\underline{/120^\circ} = -60 + J104.0$$

When the line contactor is closed, the voltage shift of the neutral may be determined by the formula:

$$V_{ON} = \frac{E_{OA}Y_1 + E_{OB}Y_2 + E_{OC}Y_3}{Y_1 + Y_2 + Y_3}$$

where Y_1 = Admittance of phase A

Y_2 = Admittance of phase B

Y_3 = Admittance of phase C

$$Y = \frac{1}{Z} = \frac{1}{R + JX} = \frac{R}{Z_2} - J\frac{X}{Z_2}$$

IMPEDANCES: ADMITTANCES:

$Z_A = 5+J3=5.84;\ Y_1=\frac{5}{34}-J\frac{3}{34}=0.147-J0.088$

$Z_B = 8+J3=8.54;\ Y_2=\frac{8}{73}-J\frac{3}{73}=0.110-J0.041$

$Z_C =10+J3=10.4;\ Y_3=\frac{10}{109}-J\frac{3}{109}=0.092-J0.0275$

Summation of Y's $=0.349-J0.1565$

$E_{OA}Y_1 = (120+J0)(0.147-J.088)=17.60-J10.60$

$E_{OB}Y_2 = (-60-J104)(0.110-J.041)=-10.88-J8.96$

$E_{OC}Y_3 = (-60+J104)(0.092-J.0275)=-2.65-11.20$

Summation of EY's $=4.07-J8.36$

$$V_{ON} = \frac{4.07 - J8.36}{0.349 - J0.1365} = 18.0 - J16.6$$

Solution for line currents:

$$\begin{aligned} I_A &= (E_{OA} - V_{ON})\,Y_1 \\ &= (120 + J0) - (18 - J16.6)(0.147 - J0.088) \\ &= (120 - 18 + J16.6)\ (0.147 - J.088) \\ &= (102 + J16.6)\ (0.147 - J.088) \\ &= 16.46 - J6.54 = 17.7\,\underline{/-21.7^\circ} \end{aligned}$$

$$\begin{aligned} I_B &= (E_{OB} - V_{ON})\,Y_2 \\ &= (-60 - J104) - (18 - J16.6)(0.110 - J.041) \\ &= (-60 - J104 - 18 + J16.6)(0.110 - J.041) \\ &= (-78 - J87.4)\ (0.110 - J.041) \\ &= -12.16 - J6.4 = 13.7\,\underline{/-152.2^\circ} \end{aligned}$$

$$\begin{aligned} I_C &= (E_{OC} - V_{ON})\,Y_3 \\ &= (-60 + J104) - (18 - J16.6)(0.092 - J.0275) \\ &= (-60 + J104 - 18 + J16.6)(0.092 - J.0275) \\ &= (-78 + J120.6)(0.092 - J.0275) \\ &= -3.85 + J13.24 = 13.8\,\underline{/106.2^\circ} \end{aligned}$$

The transient value of terminal voltage may be determined by multiplying each phase current by the load impedance of each phase.

$$V_{NA} = 5 \times 17.7\,\underline{/-21.7^\circ} = 88.5\,\underline{/-21.7^\circ}$$

$$V_{NB} = 8 \times 13.7\,\underline{/-152.2^\circ} = 110.0\,\underline{/-152.2^\circ}$$

$$V_{NC} = 10 \times 13.8\,\underline{/106.2^\circ} = 138.0\,\underline{/106.2^\circ}$$

The average of these transient voltages is:

$$\frac{88.5 + 110 + 138}{3} = 112 \text{ volts}$$

The regulator reacts to bring the average voltage up to the desired level which, for approximation only, will be an additional 8 volts per phase. The steady-state terminal voltages will now be:

$$V_{NA} = 96.5 \angle -21.7°$$

$$V_{NB} = 118.0 \angle -152.2°$$

$$V_{NC} = 146.0 \angle 106.2°$$

The percentage of voltage imbalance will be:

$$\frac{100 \times (146 - 120)}{120} = \frac{2600}{120} = 21.6 \text{ percent}$$

Comparing this magnitude of imbalance with that obtained in problem 3, it becomes evident that, whenever there is a neutral conductor, the percentage of voltage imbalance will be greatly reduced. If there were no internal impedance in the voltage source, the voltage imbalance could be reduced to zero under all load conditions by use of the grounded neutral.

In all the examples shown it will be noted that the voltage on the lightly loaded phases will be excessive, while that of the heavier loaded phase will be below normal. Operation of additional loads, both single-phase and polyphase, will be seriously affected by this imbalance.

NOTE: The problems presented in this section are intended only as a teaching aid in order to show the effects of imbalance under various circuit conditions. The voltages and degree of imbalance should not be accepted as being the exact values that would result under actual conditions. In order to take into account the transformer action that exists between phases of the generator, which alters terminal voltages, the solution would have to involve the use of positive, negative, and zero sequence components of an unbalanced circuit.

CORRECTION FOR UNBALANCED LOAD CONDITIONS

The best correction for unbalanced load conditions is to prevent this condition from occurring. Considerable effort is put forth by aircraft electrical system designers to insure that the minimum possible degree of imbalance exists under all flight conditions.

However, when the operative loads of the aircraft cannot be distributed on the polyphase system so as to maintain the desired voltage balance, dummy loads are placed on the lightly loaded phases in order to balance the total volt-amperes. This is especially true for inverters, which are more susceptible to imbalance than the larger a-c generators.

CHAPTER 6

ALTERNATING-CURRENT MACHINERY

ROTATING-FIELD A-C GENERATORS

Many a-c generators currently used in naval aircraft are of the rotating-field stationary-armature type. Generators of this design offer a number of distinct advantages.

Those windings from which generated power is taken are designated as armature windings. If the armature is the rotating member, heavy sliprings and brushes are required to carry the load current from and to the armature. Aside from other problems that arise from brushes and sliprings, such as arcing which causes radio interference, most of the generator preventive maintenance is caused by brush wear. At high altitudes, common carbon brushes deteriorate in a very short time—a condition which requires special composition carbon brushes or an elimination of their use altogether. Partly because of the problem of brush wear, the generator has been constructed so that the armature is the stationary member and the exciter is the rotating member.

When the armature is the stationary member, current supplying the load is connected directly eliminating a major source of trouble. Although the stationary armature type generator requires sliprings to supply current to the rotating field, field current is small (when compared to armature current) and results in less trouble. Even so, brushes require considerably more attention than does any of the other generator hardware. And, for this reason, brushless generators have been perfected so that the need for brushes have been eliminated. (Brushless generators are discussed in AE 3 & 2, NavPers 10348-C, chapter 8.)

An additional advantage of the armature being the stationary member results from the geometric construction of the stator and the rotor. The slots in the stationary armature can be made deeper and wider permitting larger windings and more insulating material without an overall increase in the physical size of the generator.

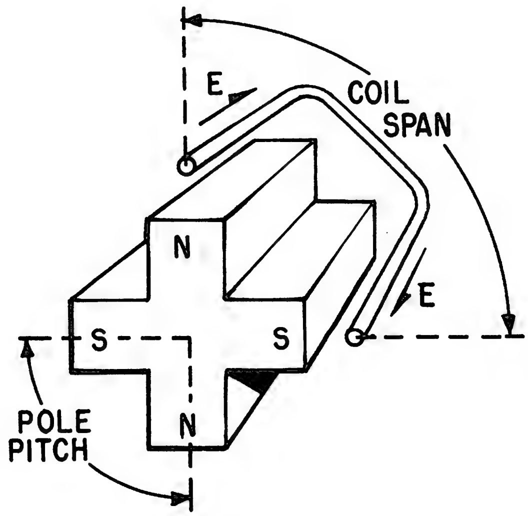
GENERATOR WINDINGS

The fundamental principles which apply to a-c generator windings are the same as those applying to d-c generators. That is, the span of any generating coil must be equal, or nearly so, to the pitch between adjacent field poles. The terms coil span and pole pitch are explained in figure 6-1. It can also be seen in figure 6-1 that when coil span and pole pitch are equal, the two sides of a coil are centered over field poles of opposite polarity. Thus, the coil sides induced voltages are additive around the coil loop.

In addition to consideration given the span and placement of the coils, all the coils making up a generating phase must be connected in such a way that coil loop emf's are also additive. Further, it is important that the coils be designed so that the wave of generated voltage is as nearly sinusoidal as possible.

Single-Phase Windings

These windings are not used in modern aircraft a-c generators. A single-phase machine



AE.500

Figure 6-1.—Relation of coil span to pole pitch.

has only about 60 percent of the power rating of a 3-phase machine of equal weight. For this reason, generators are constructed and wound 3-phase. However, loads requiring single-phase power may be connected line-to-neutral on a 3-phase wye-connected generator.

The single-phase winding is explained merely as an aid in understanding the 3-phase winding. This is possible because a 3-phase winding may be treated simply as three single-phase windings placed symmetrically around the armature frame. Therefore, an understanding of a single-phase winding is of considerable help in understanding the 3-phase winding.

Figure 6-2 represents a simple half-coil, single-layer, single-phase a-c generator. Each coil side consists of a belt of four conductors. There are two coils, though they bear little resemblance to a coil as it is usually visualized. Since there are four field poles, there are half as many complete armature coils as field poles, hence, the term half-coil is derived.

The term single-layer is derived from the fact that there is only a single conductor or conductor group, per slot. Coil 1 occupies slot belts A and B, while coil 2 occupies slot belts C and D. Keeping in mind the requirement that the two sides of a coil must lie under field poles of opposite polarity, it can be seen that two additional coils could be added to the generator. The additional coils may be placed to span slot belts B and C, and belts A and D. The generator would then be a whole-coil 2-layer type. That is, there would be as many armature coils as field poles, and two conductors in each slot. The whole-coil 2-layer type of construction is used extensively in aircraft a-c generators.

In a 3-phase generator, there are as many coils in each phase as there are field poles. When the generator in figure 6-2 is improved by deepening its slots and adding additional coils, it appears as shown in figure 6-3. The drawing is simplified to avoid confusion. Note how the coils must overlap.

Since the number of generating conductors is doubled, the output emf of the generator is also approximately doubled, assuming coils 3 and 4 were connected in series with coils 1 and 2 which were already on the generator. Had coils 3 and 4 been connected in parallel to coils 1 and 2, the output emf would have remained the same and the current capacity

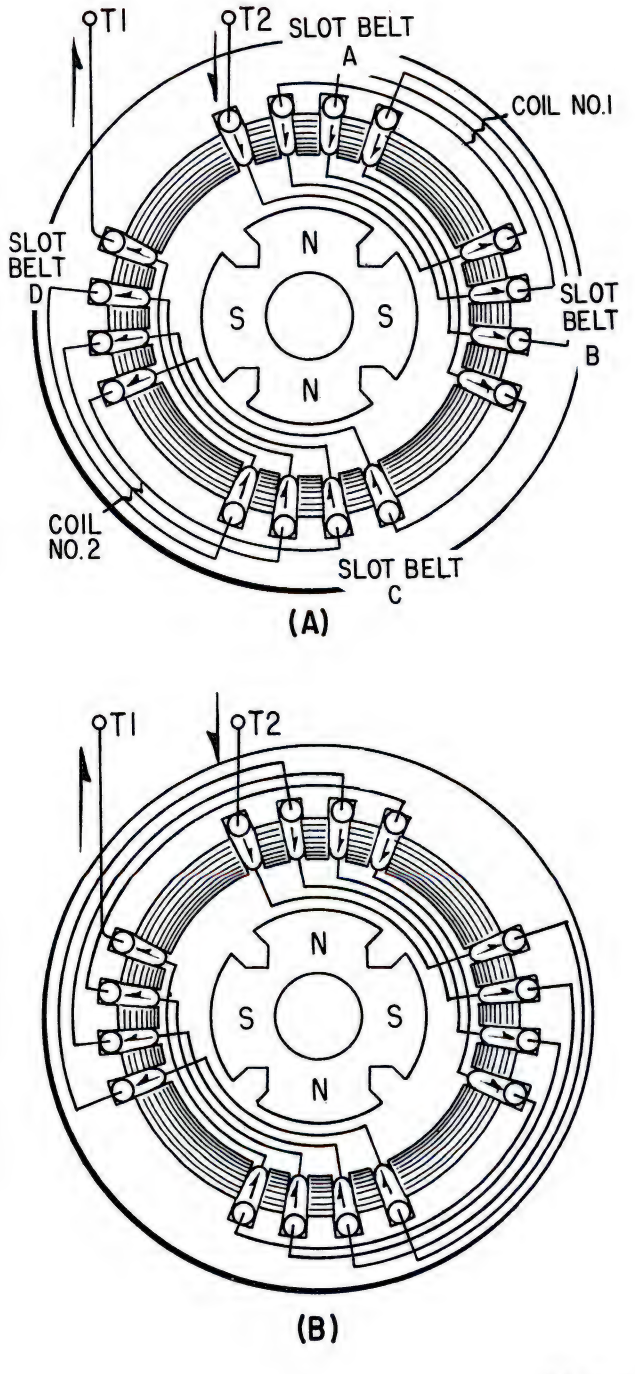


Figure 6-2.—(A) Simple lap-wound generator; (B) simple wave-wound generator.

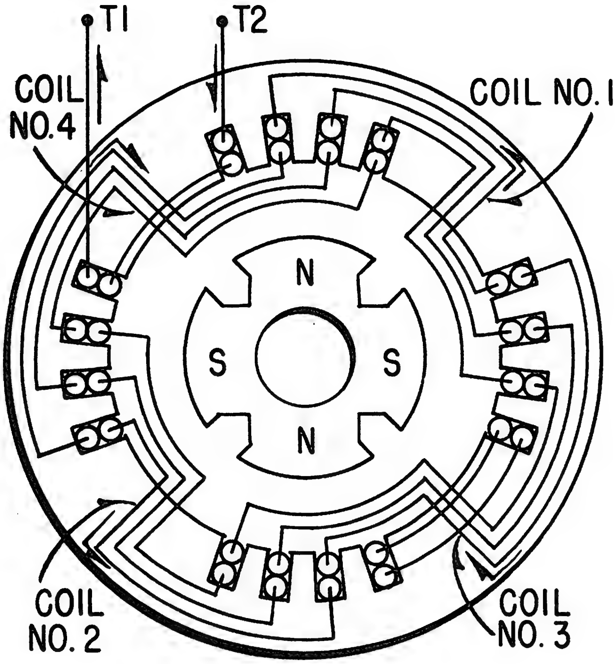


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Figure 6-3.—Single-phase whole-coil 2-layer generator.

would have been doubled. In either case, the efficiency of the generator has been improved by more efficient utilization of the available generating copper space in the armature.

In the simple machines shown in figures 6-2 and 6-3, however, there still remains wasted space between conductor belts. These features will never be encountered in practical machines. Instead, the entire face of the armature will be utilized. There will be a continuous series of slots around the armature face, and each slot is as deep as practical.

The efficiency of those machines shown in figures 6-2 and 6-3 could thus still be further improved by slotting the wasted armature space, and adding still more coils, thus forming additional phases. Before entering into a discussion of the more complex machines, it is necessary to present a simple method of depicting their winding layout. This method is explained in figure 6-4.

Figure 6-4 (a) depicts a simple machine whose windings are illustrated in the same manner used thus far. If the generator were broken at the fracture lines shown in (A), and then unrolled, it would appear as shown in (B).

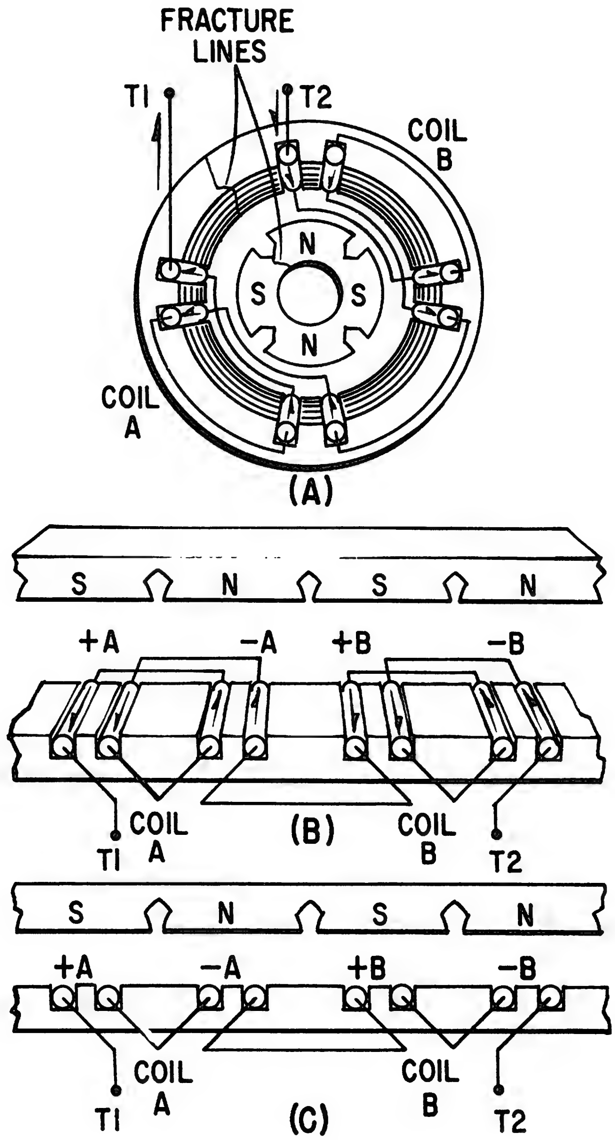

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Figure 6-4.—Development of simplified winding layout.

Note that only the shape is changed. That is, conductor groups still lie beneath the same poles, direction of induced emf is the same, and connections at both ends of the conductors are still shown. Also in (B), an additional illustrative feature is introduced. Note that the side of coil A that lies beneath a south field pole is labeled +A, and its other side, beneath a north field pole, is labeled -A. Coil B is labeled in a

similar manner. This labeling pertains to the direction of induced emf in the coil sides. It serves an additional purpose in figure 6-4 (C); the connections between conductors are visible only at one end of the conductors. If the two conductor groups bear the same labeling letters, such as +A and -A, then the viewer can assume that the two groups are interconnected at their hidden ends. However, in a 3-phase generator, all the conductors in a phase, comprising more than just two groups, may be labeled with the same letter. In this way, where there are a great number of conductors, those conductors comprising one phase may be picked out when it is desired to analyze the winding pattern for a given generator.

Three-Phase Generators

Figure 6-5 represents a 3-phase, half-coil, single-layer, 4-pole, a-c generator.

The armature face is slotted continuously, with a total of 36 slots. Since there are 3 phases, and one-third of the slots are allotted to each phase, then there are 12 slots for each phase. Being a 4-pole machine, the generator thus has three slots per pole per phase. That is, each phase is distributed in belts around the armature in such a way that an equal number

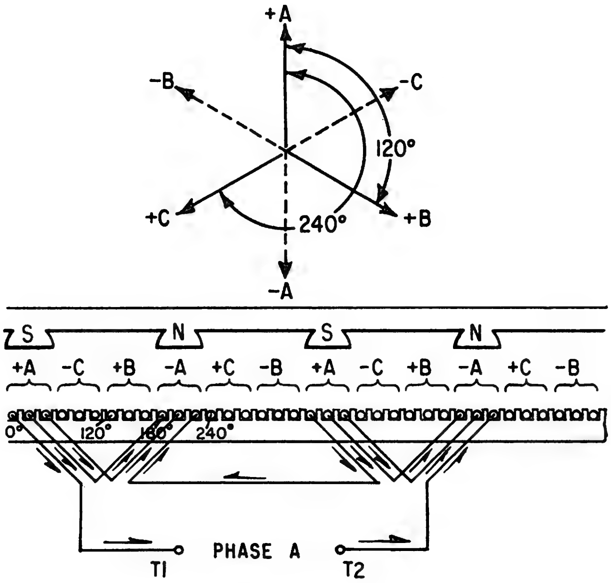

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Figure 6-5.—Three-phase, half-coil, single layer, 4-pole, a-c generator.

of conductors, or slots, of that phase lie beneath each field pole. Note that all belts of a phase lie directly under their respective field poles at a given time. In figure 6-5, all belts of phase A are in this position, so that at the instant shown, the emf of phase A is maximum. All 12 conductors are connected additively so that their emf's combine, as shown by the arrows. Their combined value appears across the terminals T1 and T2. For simplicity, the end connections for phase B and C are not shown. (If shown, they would appear exactly as those for phase A.)

Successive belts are 180 electrical degrees apart, since they lie beneath opposite field poles. The first conductor in a +A belt is 180° ahead of the first conductor in a -A belt. They are 10 slots apart. If slot 1 is considered as 0°, and slot 10 is 180°, then there are 9 slots, or steps, between them. Therefore, the electrical pitch for each slot is 20° (180°/9 = 20°).

If the phase rotation of a generator is ABC, this means that the phases of that generator must pass their positive peaks in that sequence, 120° apart. The rotation for the generator in figure 6-5 is ABC. Starting with phase A at peak positive, as shown, then phase B should be 120 electrical degrees away. That is, starting with the first conductor in a +A belt at a given place, then the first conductor in a +B belt should lie in a slot 120 electrical degrees away. This condition exists in figure 6-5. Slot 1 contains the first conductor of a +A belt, and slot 7 contains the first conductor of a +B belt. Starting at slot 1, there are six steps to slot 7. Since each slot, or step is 120°, then the two conductors are 120° apart (20° x 6 = 120°). Since the positive peak voltage in phase C must occur 240° after the peak in phase A, then the first conductor in a +C belt should lie 240° away from the first conductor in a +A belt. This condition also exists in figure 6-5. The first conductor in a +C belt lies in slot 13, or 12 steps past slot 1. It is, therefore, in its proper electrical position of 240° (20° x 12 = 240°).

After locating the plus sides of the coils, it is a simple matter to locate the minus sides, because the two sides of any coil must lie 180° apart, in a full-pitch winding. (The difference between full-pitch and fractional-pitch winding is discussed later.) It will also help if the ordinary 3-phase vector is kept in mind. Referring once more to figure 6-5, note that the vectors are in the same sequence as the generator windings. Starting with +A and progressing

around the vectors in a clockwise direction, the vectors are encountered in the same sequence as starting at the first +A conductor belt in the generator and progressing to the right.

Figure 6-6 represents a more practical generator that may be developed from the one in figure 6-5. There are still 36 slots, and 3 slots per pole per phase. However, the slots have been deepened and one more coil added. The generator has thus become a whole-coil, 2-layer machine. By starting at T2 in figure 6-6 and tracing the path of emf indicated by the arrows, the entire phase, including all 24 slot conductors, will have been traversed by the time T1 is reached. Despite its rather complex appearance, the entire phase A is a single series path between T1 and T2. If the end connections for phases C and B were shown, there would be three complete traceable paths through the generator; one for each phase.

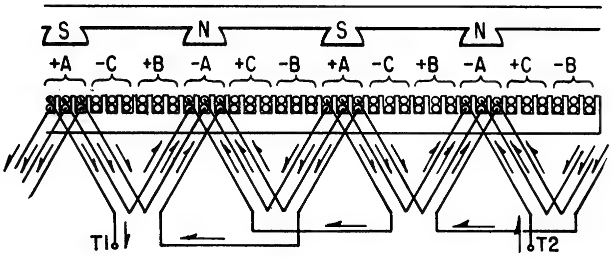

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Figure 6-6.—Three-phase, whole-coil, 2-layer, 4-pole, a-c generator.

In practice, small a-c generators normally have a single series path through each phase. However, large machines will generally have a combination of parallel paths comprising each phase. In this way, individual coil conductors are not required to be of sufficient size to carry the full line current, as they would in a series connected arrangement. The phase terminal voltage is the same as any parallel coil voltage, but each coil current is only a fraction of the total phase current.

In some a-c generators, the armature coils do not span a full 180 electrical degrees. That is, when one coil side is directly under a field pole, the other side does not lie fully centered under an opposite pole. This is known as a fractional-pitch winding. A generator wound in this manner is shown in figure 6-7.

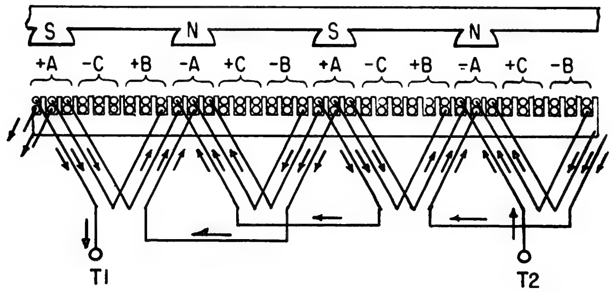

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Figure 6-7.—Three-phase fractional-pitch generator.

The fractional-pitch winding type generator is similar in all respects to the one shown in figure 6-6 except that the entire bottom layer of conductors has been slipped back one slot. As previously determined, the electrical pitch between slots is 20°, so that the span of any coil is now 160° (180° - 20° = 160°). The coil sides obviously no longer reach their respective peak and zero positions simultaneously. As a result, the effective output of the generator is somewhat reduced.

In determining the voltage generated in a fractional-pitch coil, the pitch factor must be considered. For an explanation of the pitch factor, refer to figure 6-8.

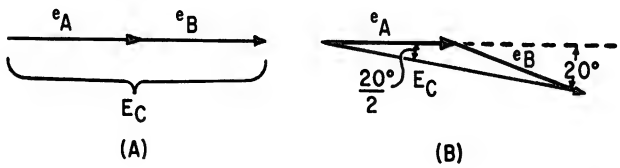

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Figure 6-8.—(A) Full-pitch coil emf; (B) fractional-pitch coil emf.

Figure 6-8 (A) represents the emf's in a full-pitch coil. The total coil emf (E_C) is obviously twice either coil side emf, or E_C = 2eA or 2eB. In part (B), however the coil side emf's are not a full 180° apart. If part (B) represents the emf of any coil in the generator shown in figure 6-7, where the coil pitch is only 160°, then E_C must be somewhat less than in part (A) because eB has not reached its peak at the

instant shown. It lacks 20°. Consequently, E_C in part (B) is

$$E_C = 2eA \cos \frac{20^\circ}{2}$$
$$= 2eA \cos 10^\circ$$
$$= 2eA \cos (0.984)$$

The pitch factor for the generator in figure 6-7 is thus shown to be 0.984.

The loss of generated voltage is more than compensated for by at least four additional effects of the fractional-pitch winding. These advantages may be stated as follows:

1. The coils are narrower and less copper is required in the end connections.
2. There is less inductance in a coil, because certain of its conductors occupy slots which also contain conductors of other phases.
3. The waveform of generated voltage is improved.
4. Harmonics are greatly reduced.

In fact, the ninth harmonic for the generator in figure 6-7 is eliminated entirely, because its fraction of winding is eight-ninths (160°/180° = 8/9). In a 5/6 pitch winding, the sixth harmonic is eliminated, in a 4/5 pitch winding the fifth, and so on.

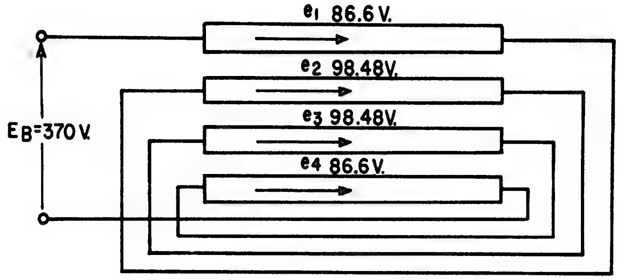
An additional factor that affects generated emf must be considered when phase belt conductors are distributed in a number of slots. Figure 6-9 represents a 4-conductor belt which is exactly centered under its field pole. If the four conductors are connected in series additive, the belt emf must obviously be at maximum at the instant shown. Assuming each conductor generates a peak of 100 volts, then the belt emf would be 400 volts if all conductors reached their peaks simultaneously. Of course, they cannot do this because they are spaced 20 electrical degrees from each other. Total belt emf is the sum of the 4-conductor emf's and each conductor emf may be computed if it is known how many electrical degrees each conductor lies away from its peak.

In figure 6-9, the emf of conductor 1 or 4 is

$$e_1 \text{ or } e_4 = 100 \sin (90^\circ - 30^\circ)$$
$$= 100 \sin 60^\circ$$
$$= 100 (0.866)$$
$$= 86.6 \text{ volts}$$

The emf of conductor 2 or 3 is

$$e_2 \text{ or } e_3 = 100 \sin (90^\circ - 10^\circ)$$
$$= 100 \sin 80^\circ$$
$$= 100 (0.9848)$$
$$= 98.48 \text{ volts}$$



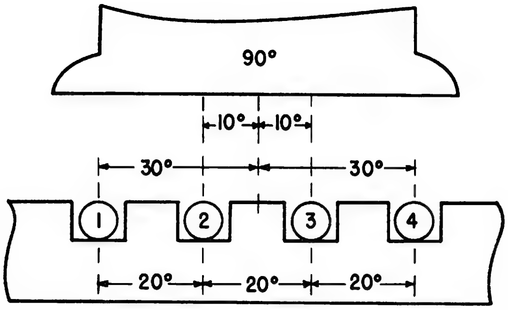


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Figure 6-9.—Belt factor of distributed windings.

The total peak belt emf is

$$E_B = e_1 + e_2 + e_3 + e_4$$
$$= 86.6 + 98.48 + 98.48 + 86.6$$
$$= 370 \text{ volts (approx.)}$$

It can be seen that the emf is reduced from 400 volts, where the conductors are concentrated, to 370 volts, where they are distributed. This effect is referred to as the breadth or belt factor, and is symbolized by K_B. It must be included when computing generated voltage. The belt factor for the phase belt shown in figure 6-9 is

$$K_B = \frac{370}{400} = 0.925$$

For further clarification, total phase emf is computed for the generator shown in figure 6-7, which will involve both the pitch factor K_P and belt factor K_B. The pitch factor has already been determined as 0.984. Assuming peak conductor emf is 10 volts, the belt factor for the 3-conductor groups is determined as follows: The center conductor is at a peak of 10 volts. The remaining two conductors are

each 20° away from peak, so their instantaneous emf is

$$\begin{aligned} e &= 10 \sin (90° - 20°) \\ &= 10 \sin 70° \\ &= 10\ (0.9397) \\ &= 9.4 \text{ volts (approx.)} \end{aligned}$$

The belt factor is

$$\begin{aligned} K_B &= \frac{9.4 + 10 + 9.4}{10 + 10 + 10} \\ &= \frac{28.8}{30} \\ &= 0.96 \end{aligned}$$

Since there are a total of 24 series-connected conductors, total phase emf across T1 and T2 is

$$\begin{aligned} E_T &= 10 \cdot 24 \cdot K_P \cdot K_B \\ &= 10 \quad 24\ (0.984)\ (0.96) \\ &= 226 \text{ volts (approx.)} \end{aligned}$$

Generator Construction

ARMATURES.—When in operation, the iron in the armature is continuously cut by the alternating field flux. As a result, eddy currents are induced in the iron, causing heat and flux pattern distortion. To minimize eddy currents, the armature is built up of a great number of thin layers, each partially insulated from the other. By confining the eddy currents in this manner, their total detrimental effects are greatly reduced. This method of construction is referred to as lamination. To construct a generator in this manner, circular or semicircular pieces with the same form as a cross section of the finished armature are punched out of thin sheets of iron. The armature is then constructed by taking the punchings and bolting them together. The armature iron is further supported by an outer steel frame of generally cylindrical shape, or bound together by steel clamping bands. In some cases, the laminations are encased between heavy steel end plates.

If required by design specifications, the armature may have ventilating ducts running through the iron for cooling purposes. As a rule, small generators are cooled sufficiently by air passage through the winding and slot spacing, and do not require ducting. Aircraft generators utilize cooling air impellers as an integral part of the rotor and employ blast tubes which force cooling air through the generator. In recently developed brushless generators, a system of ports are used for oil cooling. It is important that the heat distribution be uniform throughout the armature, to avoid hotspots which would limit the rating of the machine. The rating of a machine is linked directly to the internal temperatures it can withstand.

SLOTS.—Armature slots may be either of two types—open, or semiclosed. The open type, shown in figure 6-10 (A), lends itself readily to ease of manufacture, since coils may be inserted in the slots as a package, often being wound, formed, and insulated separately. However, generators of open-slot construction have certain undesirable characteristics, such as flux tufting and distortion, which make them unsuitable for widespread use in aircraft. Use of the semiclosed type as shown in figure 6-10 (B) is nearly universal in naval aircraft. With this type of slot there is less distortion of the airgap flux between field and armature, and consequently less rippling and distortion of the generated wave.

In both types of slots, the windings must be held securely in place because of vibration and electromagnetic stress. This is usually accomplished by utilizing wedges.

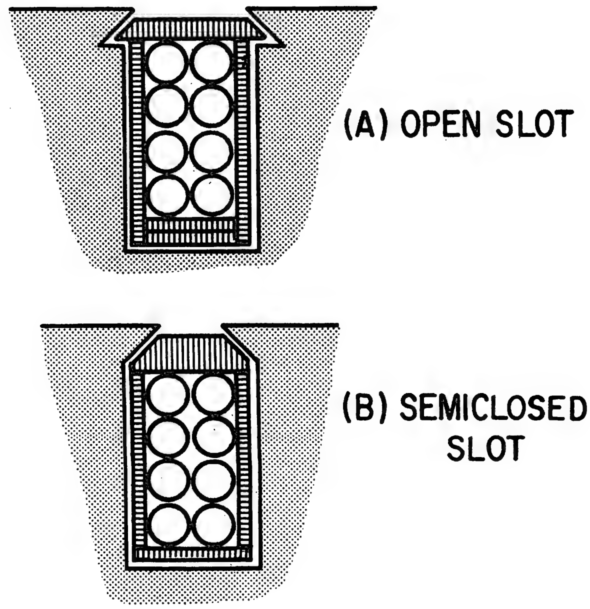

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Figure 6-10.—(A) Open slot; (B) semiclosed slot.

Coil insulation falls into two general categories—organic base, or mineral base. The organic types are identified as class A, and include such materials as cambric and paper. When impregnated by varnish, class A insulation is limited to an operating temperature of about 100°C. Class B, or mineral insulation, includes materials such as asbestos, mica, and Fiberglas. When these materials are impregnated with silicone base varnishes, their operating temperature is about 160°C.

In practice, generating coils are not single conductors, but are formed from a multiple of small conductors. The conductors nearer the top of a slot have less self-inductance than those at the bottom. This is true because the conductors at the bottom are effectively more completely surrounded by iron, and have more inductance, while those at the top are nearer the open slot gap, and have less inductance. Consequently, current tends to flow more readily in the top conductors. This unequal inductance may be eliminated by the method in which a coil is wound. If the first conductor lies at the bottom, the second should be in the middle, and the third should be at the top. This process is carried out until the coil is completed. Another method of obtaining uniform current distribution is by twisting the conductors. To insure that each conductor offers a separate current path, the conductors are coated with insulating enamel.

ROTARY FIELDS.—Rotating fields are a-c generators in general may be constructed in either of two ways: First, there may be a solid steel rotor in which the field windings are imbedded; or, second, there may be a central steel frame to which separate laminated pole pieces are attached. The second type is the salient-pole construction, and is required by military specifications to be used in aircraft a-c generators. The use of this type construction permits a better power rating for a given generator, because the rotary field is more easily cooled. There is space for the passage of air between the salient poles, and their own inherent fanning action works to dissipate excessive heat. Heat is the greatest limiting factor in the rating of a generator.

Military specifications also require that the field excitation power for a generator be produced within the machine itself. This keeps the a-c generator from being dependent on an external source for its d-c field. For this reason, a d-c exciter generator armature is built on the same drive shaft as the a-c generator's rotating field.

PHASING GENERATOR WINDINGS.—The two ends of each phase in an a-c generator are brought out to a pair of external terminals. Therefore, there are three pairs of terminal studs on the terminal block of a 3-phase generator. These a-c terminals are the "T" terminals and are readily identified when inspecting an a-c generator. Other terminals on the block are for exciter control. The attached plate shows internal connections for a particular generator so that it can easily be determined which terminals constitute pairs, or opposite ends of each coil. By connecting short jumpers between the external terminals of different phases, the generator may be made to operate in either delta or wye. Only the wye connection is discussed, since naval aircraft generators are not operated in delta.

Assume that an inspection of the plate which shows internal connections indicates that paired terminals are T4 T1, T5 T2, and T6 T3, as shown in figure 6-11, and it is desired to operate a generator in a 4-wire wye system. Phase voltage is 100 volts. The first step is to connect a jumper between single ends of any two pairs of terminals, such as T4 and T5, with the generator running. A voltage reading taken across T1 and T2 should then be 100 $\sqrt{3}$, or 173 volts. If it is only 100 volts, either coil must be reversed. Next, connect T6 to the junction of T4 and T5. Voltage checks from T3 to T1 and T3 to T2 should also read 173 volts. If not, the last coil connected (T6 T3) should be reversed. At this point, the wiring may be connected to the generator, observing the proper phase rotation. Terminals T1, T2, and T3 should be connected to the phase powerlines, and the common wire connected to the junction of T4, T5, and T6.

A-C ELECTROMOTIVE FORCES AND OUTPUTS

FACTORS AFFECTING A-C GENERATOR TERMINAL VOLTAGE

When an a-c generator is operating properly, but with no load connected, the terminal voltage is the same as the voltage being induced into its windings. When a load is connected, however, the resultant flow of current through the armature causes a number of things to happen. The

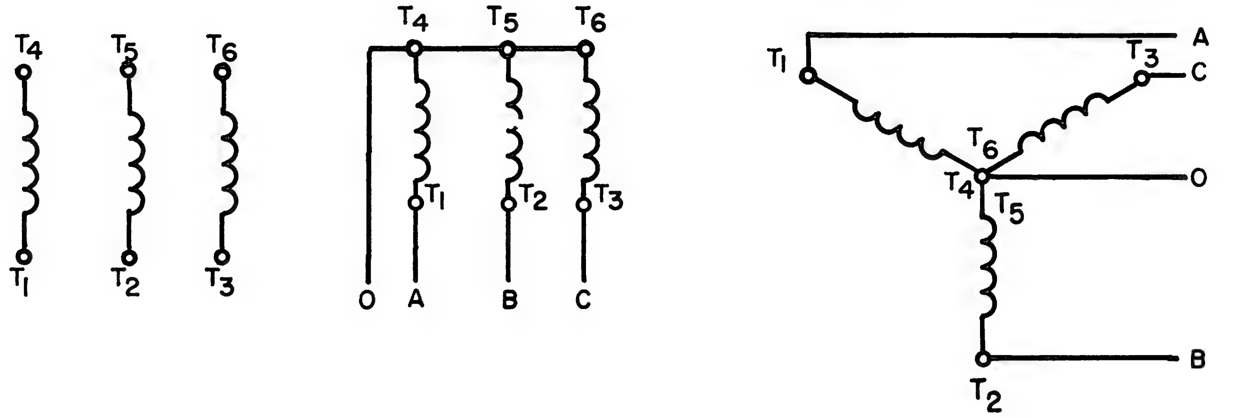

Figure 6-11.—Terminal connections.

net result of these operating characteristics is that terminal voltage assumes a different magnitude, and moves out of phase with the generator's fundamental induced voltage. One such characteristic is the resistive voltage drop across the armature.

Armature Resistance

When current flows through the armature conductors, each conductor is surrounded by a resultant magnetic flux. The flux of all the conductors in a slot becomes linked into a single larger magnetic field. This flux flows freely in the low-reluctance iron surrounding the slot, and is referred to as leakage flux. It is an alternating flux, and results in eddy currents and hysteresis; these affect the iron by causing it to heat. These local losses vary nearly as the current squared, and so closely resemble losses caused by the simple copper ohmic resistance. Their effect is one of increased resistance, and accounts for a greater effective resistance to alternating current flow than to direct current. In practice, the total resistive (heat) loss in an armature is extremely small when compared to losses caused by armature reactance and armature reaction.

Armature Reactance

Because there are excellent linking conditions for conductor leakage fluxes, the inductive reactance of generator windings is very high in relation to their effective resistance. The combined loss caused by the effective resistance and inductive reactance is commonly referred to as the armature impedance loss, or synchronous impedance.

Armature Reaction

When there is no current flowing in the generator armature, there are no opposing or distorting influences working against the airgap flux supplied by the field. With the start of armature current flow, however, the armature conductors set up a magnetomotive force of their own, because of the current flowing through them. It is an alternating mmf because its parent current is an alternating current. This mmf is responsible for the inductive reactance of the armature. In addition, this same mmf reacts with the field flux. It may only distort the field, or airgap flux, or it may directly oppose and materially weaken it. If conditions are right, it may even aid and strengthen the airgap flux.

In any of these three above cases, however, it obviously has definite effects on terminal voltage. The effect that the alternating armature mmf has on the airgap flux is determined by its timing in relation to the moving field poles. Its timing is determined by the reactive characteristic of the generator's load. This may be resistive, inductive, or capacitive. The effects of each type load are discussed.

LOADING CHARACTERISTICS

Figure 6-12 shows the various effects caused by different reactive-characteristic loads. Part (A) represents a generator whose armature emf and current are in phase. Emf is at its peak value because the coil sides are directly under the field poles. Since current is in phase, then the coil mmf is also at its instantaneous peak simultaneously. Note that the effective center of the coil mmf is acting on the space between the field poles. Therefore, the pole flux is distorted somewhat, but not materially weakened.

In figure 6-12 (B), a highly inductive load is connected to the generator, so that current lags the coil emf by 90°. Peak induced emf occurred 90° before the instant shown, when coil side A was under a north pole. Peak mmf exists 90° later, as shown. As a result of this timing, the peak magnetomotive forces of the coils occur directly under the field poles and are of opposite polarity to them. As a result, the airgap flux is materially weakened, and output voltage is reduced. In part (C) a capacitive load is connected to the generator, so that current leads the coil emf by 90°. Note in part (C) that conditions which existed in coil side A 90° after peak emf occurred in part (B), now exist 90° before peak emf occurs. Again, as a result of this timing, peak coil mmf occurs directly under the field poles. However, with current leading, the coil mmf aids the field pole flux, and a greater induced voltage results.

From the foregoing, it can be seen that three major factors affect the terminal voltage of an a-c generator. For a fixed magnitude of load current, the armature resistance loss (IR) and armature reactance loss (IX) are fixed, regardless of load reactive characteristics. However, the effects of the third factor, armature reaction, depend greatly on load characteristics. The vector diagrams in figure 6-13 show how

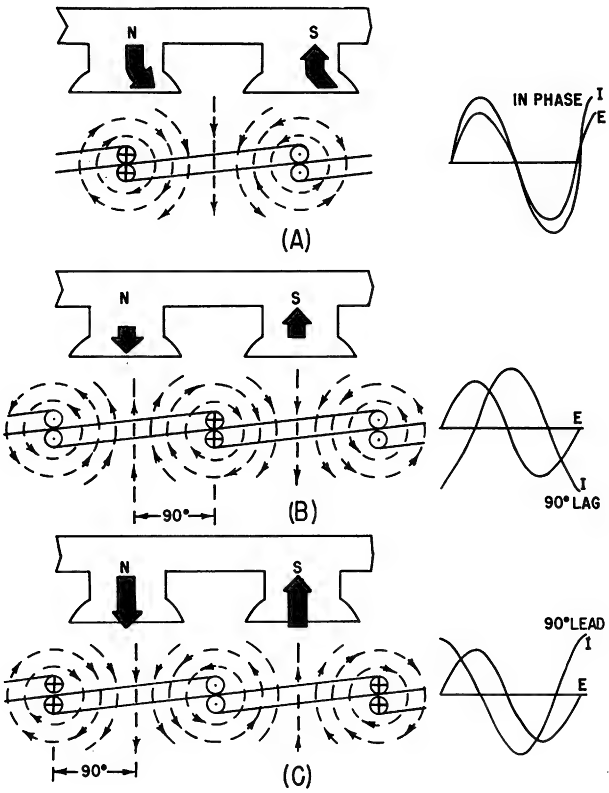

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Figure 6-12.—Effects of load on airgap flux pattern.

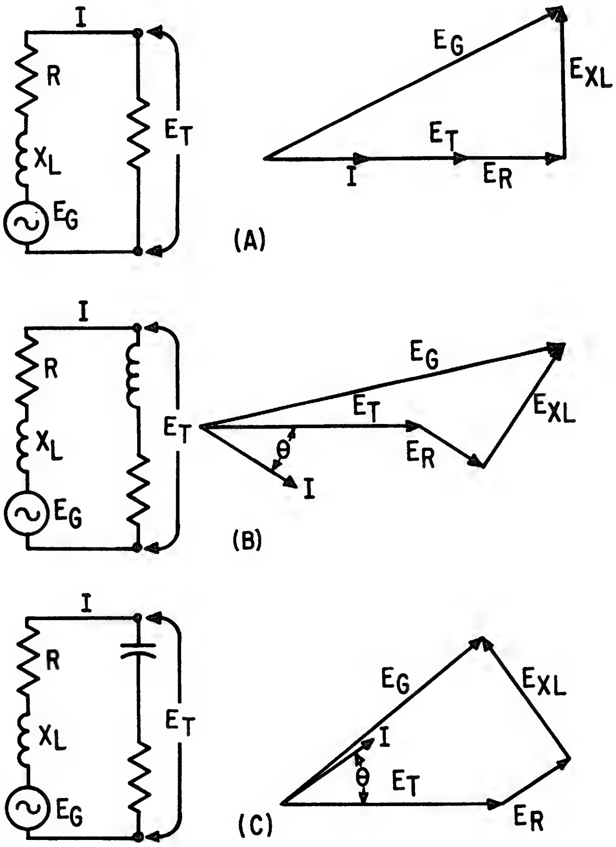

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Figure 6-13.—(A) Resistive load; (B) inductive load; (C) capacitive load.

various load characteristics tend to affect terminal voltage.

The word tend is used because terminal voltage is controlled and fixed by the voltage regulator. Since terminal voltage is held constant, then the variable quantity is the fundamental induced voltage. Changes in induced voltages are accomplished through changes in the magnetic strength of the rotating field. Figure 6-13 (A) depicts a generator whose internal winding reactance is X_L and whose winding resistance is R. The load is resistive, so terminal voltage E_T and line current I are in phase. The fundamental induced voltage E_G must be the vector sum of terminal voltage plus the internal drops E_{XL} and E_R. This is shown in the vector diagram. Note that the armature resistance drop E_R is in phase with the current, because it is a direct result of that current. The reactance drop E_{XL} is laid out 90° leading, as usual. Total induced voltage E_G is the hypotenuse of a triangle whose base is E_T plus E_R, and whose altitude is E_{XL}.

In part (B) of figure 6-13, the magnitude of load current I is the same, but it now lags E_T by θ, due to the inductive load. The magnitude of E_R and E_{XL} has also remained unchanged. However, by remaining in phase with or following the current, E_R has tilted the winding impedance loss triangle so that E_G was required to increase its length in order to allow E_T to remain constant. What this amounts to, when applied to actual generator operation, is that the inductive load caused the timing of the armature mmf to weaken the field flux. The voltage regulator then caused a greater field current, and thus increased E_G in order to hold E_T constant. It is to be noted that the magnitude of load current is the same in part (A) and part (B), yet a greater field control power was required when an inductive load replaced the resistive load.

In figure 6-13 (C), a capacitive load is connected so that line current I leads terminal voltage E_T by θ. Again, E_R follows the current direction, and the winding impedance loss triangle is tilted so that E_G became shorter in order to maintain E_T at a constant length. That is, the armature mmf timing was shifted to lead the coil emf and thus it aided and strengthened the field flux. The voltage regulator had to decrease field strength to prevent E_T from rising. Again, it is to be noted that current phase, not magnitude, was changed. It is also of interest to note that with enough capacitance in the load, the generator's induced emf may actually be less than its terminal voltage. Induced emf and terminal voltage are approximately equal when the load capacitive reactance matches the armature winding inductive reactance.

A-C GENERATOR PRIME MOVER CHARACTERISTICS

SINGLE GENERATOR OPERATION

The prime mover of an a-c generator is its source of rotational force. This force may be supplied directly by the aircraft engine, an air or gas turbine, a hydraulic motor, a constant-speed drive assembly, or an electric motor (as in the case of inverters). Whatever driving device is used, any power taken from the a-c generator ultimately is supplied by the prime mover. Therefore, the power rating of the driving device must be sufficient to supply the generator output energy, plus all losses, without excessive speed reduction. The governor of the prime mover must maintain drive shaft speed, with and without load, within the limits specified by the a-c generator's output frequency requirements.

Frequency and power controls are discussed later in this chapter.

MULTIGENERATOR OPERATION

In order for a-c generators to operate properly in parallel, their respective prime-movers must have drooping speed-load characteristics. That is, their driving devices must undergo slight decreases in rpm as load is added to the generators. This requirement exists for the following reasons.

The sloping, or drooping loadlines shown in figure 6-14 show the effects on the speed of the two generators' prime movers as the common load is varied. Prime mover speed is given as generator frequency. Starting with a no-load condition, prime mover speed, and thus generator frequency, is at a maximum value, shown as F_{NL}. As load is increased from the no load to the operating-load condition, the speed of both prime movers decreases until line frequency is at F_{OL}. An increase of load current to a full-load condition would result in a line frequency of F_{FL}. It is assumed that both prime movers have identical speed-load characteristics, so it follows that each generator

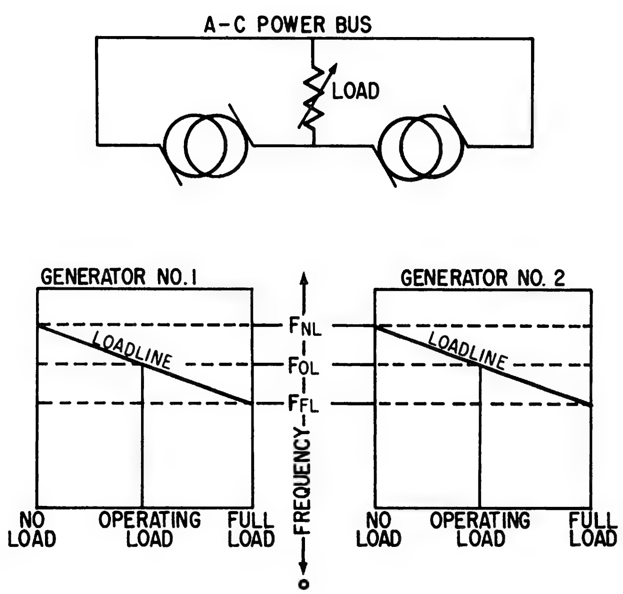

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Figure 6-14.—Speed-load curves for a-c generators operating in parallel.

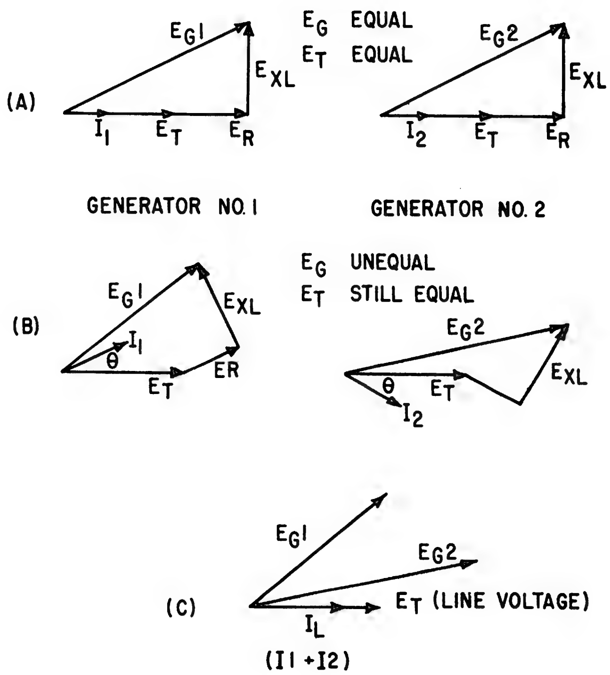

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Figure 6-15.—Effects of varying field strength in generators operated in parallel.

carries one-half of the total load. The terminal voltage and frequency of both generators must always be the same, because their terminals are connected directly together on the a-c power bus.

When a generator is operating at a certain speed with a certain load, its prime mover is delivering all the mechanical power of which it is capable with that governor setting. If it were capable of delivering any more power, it would obviously speed up. Keeping this in mind, consider the following: Assume the two generators in figure 6-15 are supplying equal parts of a normal operating load, at a frequency of F_{OL}, and at a certain line voltage. To start with, the field strength of both generators is equal. If the field current of generator No. 1 is increased, and that of generator No. 2 is decreased a like amount, line (terminal) voltage remains the same, because the increasing voltage tendency of No. 1 is counteracted by the decreasing tendency of No. 2. At a glance, it would seem that generator No. 1 would assume a greater load than generator No. 2, as would be the case if d-c generators were used. At this point, however, it must be remembered that the prime mover of generator No. 1 cannot assume any greater load. Likewise, the prime mover of generator No. 2 cannot drop any of its load, because there is no other device in the system to assume the load that is dropped, since generator No. 1 cannot do so. Therefore, it becomes apparent that the balance of power between two a-c generators cannot be effectively controlled by changes in their field strength.

A-C GENERATORS OPERATED IN PARALLEL

REACTIVE POWER

It has been stated that changing the field strength of two generators operating in parallel does not effectively change their power loads. It does, however, have certain other effects.

Figure 6-15 shows what these effects are. To begin with, part (A) represents two identical a-c generators operating in parallel whose terminal voltages are necessarily the same, and whose internal losses E_R and E_{XL} are identical. Field strength is the same in both generators, so their induced voltage E_G is the same. The load is nonreactive, so current I is in phase with terminal voltage E_T in both generators. In part (B), the field strength of generator No. 1

is decreased, and that of No. 2 is increased so that E_T is still the same. However, the induced voltage E_G has been forced to change in both generators because it is a function of field strength magnitude. For unequal induced voltages to result in equal terminal voltages, their vectors shift as shown in part (B). Current leads in the underexcited generator, and lags an equal amount in the overexcited generator. Because of this change in the timing of the individual generator currents, the armature reaction (mmf) of generator No. 1 is advanced and so does not adversely affect its airgap flux as strongly as before.

On the other hand, the armature mmf is retarded in generator No. 2, and has a greater demagnetizing effect on airgap flux than before. The net result is that the unequal induced voltages, due to the inverse and unequal effects of armature reaction, result in a common equal terminal voltage. It has developed, then, that the only visible effect of varying the generators field excitation is that current has moved out of phase with terminal voltage in both generators.

Where current leads in one generator, it lags an equal amount in the other, so power is still the same in both generators. It should be noted that these phase angles are not caused by a reactive load. Current through the load is in phase with line voltage, because load current is the sum of the two generator currents. This is shown in figure 6-15 (C). Since the generator currents lie in opposite directions an equal number of degrees away from line (terminal) voltage, their sum current phase angle across the load is zero. However, it should also be noted that any reactive characteristic in the load would affect individual generator phase angles still further. For instance, an inductive load (due to its retarding effect) would decrease the current lead in generator No. 1, but would increase the current lag still further in generator No. 2. It becomes apparent at this point that where the load is unavoidably reactive, the VARS supplied by each generator is most effectively controlled by changing the field strength of the generators. An equal distribution of reactive load (equal generator current phase angles) is obtained by changing the voltage regulator settings.

WATT DISTRIBUTION

Figure 6-16 is used to represent the sequence of reactions in two a-c generators operating in parallel with adjustments are made to their prime mover governors. It is assumed both prime movers have identical power capacities.

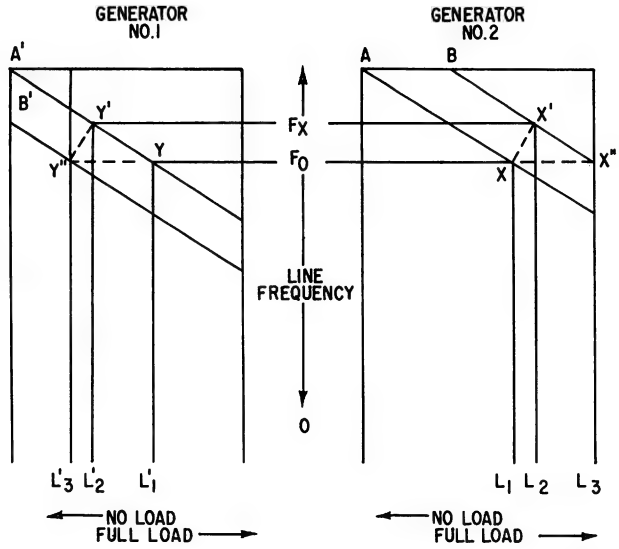

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Figure 6-16.—Effects of varying prime mover governor settings.

At the start, the generators have equal in-phase current loads, and their speed-load curves. (governor settings) A and A' are set at the same level. The line frequency is F_O, and the equal loads are L_1 and L_1'. The frequency line and load lines intersect the speed-load curves at point Y in generator No. 1 and at point X in generator No. 2.

Assume that it is desired to increase the load on generator No. 2 and decrease the load on generator No. 1, with no change in frequency. By increasing the governor setting on No. 2, its speed-load curve is raised to the level shown at B. The generator speeds up, bringing generator No. 1 up with it. (The reason for this is explained in this chapter under synchronizing power.) Line frequency is thus increased from F_O to F_X, and since the point of intersection has moved from X to X' in generator No. 2, the load has increased from L_1 to L_2. The speed-load setting for generator No. 1 was not changed, but the rise in line frequency moved its point of intersection from Y to Y', and decreased its load from L_1' to L_2'.

Since no change in frequency is allowed, the next step is to bring the frequency from F_X

back down to F_O. This is accomplished by decreasing the governor setting on generator No. 1 and thus lowering its original speed-load curve from A' down to B'. The frequency F_X decreases to its original value of F_O, and the point of intersection in generator No. 1 moves from Y' to Y", while its load decreases even further, from L_2' to L_3'. Simultaneously, the point of intersection in generator No. 2 moves from X' to X" and its load increases even further from L_2 to L_3. At this time, the adjustments are complete. The final value of line frequency is unaltered, but the load on generator No. 2 has been increased from L_1 to L_3 while the load on generator No. 1 has been decreased from L_1' to L_3'.

From the foregoing, it is apparent that the most effective means of balancing the real load, in watts, between two a-c generators is through control of their prime mover mechanical power outputs. This is accomplished by controlling the governor settings on mechanical drives, or by varying the field strength of electric-motor drives.

From the foregoing discussion of reactive load balancing and watt load balancing, it becomes apparent that both a generator's voltage regulator and its prime mover governor serve dual purposes when two generators are operated in parallel. Their voltage regulators serve to control both line voltage and the reactive load balance between them, while their prime mover governors serve to control both line frequency and the watt load balancing. These functions may be accomplished either manually, or automatically.

SYNCHRONIZING POWER

When the same phases of two generators are connected to a common bus, their terminal voltages are approximately in phase and of the same magnitude. Each phase voltage must reach its positive peak, negative peak, and zero value at exactly the same time as the other. Assuming these conditions exist, and no load is connected to the bus, then there is no current flow through either generator. However, if any influence causes one generator to speed up, such as an increase in its prime mover governor setting, the other generator will also speed up.

This occurs for the following reason. When the first generator is accelerated, its alternating voltage timing is advanced slightly ahead of the other. Consequently, its phase voltage reaches its peak and zero values slightly ahead of the other. As a result, a circulating alternating current flows across the bus and through the generators. Its effect is to slow the speeding generator by loading it and to accelerate the lagging generator by tending to motorize it. With no load on the bus, the faster generator actually drives the slower one to some extent, allowing its prime mover to speed up. Where the two effects balance, a common and higher frequency is reached.

When a load is on the bus, the overdriven generator does not motorize the other, but takes more of the load and thus limit its own increase in speed. The underdrive generator accordingly takes less load and speeds up to match the frequency of the faster generator. This interaction is referred to as the synchronizing characteristics of a-c generators, and is responsible for their strong tendency to remain locked in when operated in parallel.

REQUIRED CONDITIONS FOR PARALLELING A-C GENERATORS

Up to this point, the discussion has dealt with the operating and regulating aspects of a-c generators after they have been connected to a common bus. No mention has been made of the special requirements to be observed before connecting an additional a-c generator to a bus already being supplied by another.

In the parallel operation of d-c generators, a significant aspect to consider is that two generators with slightly unequal voltages, and whose armature rpm's are slightly unequal, may be connected to a common bus without damaging the generators. The two d-c generators divides the load between themselves so that their terminal voltages (bus voltages) are equal. At this time, their individual speeds and loads may still be unequal. From the foregoing, it is apparent that the transient synchronizing forces which act on two generators when they are interconnected produce equal terminal voltages in all cases, but speed and load may remain unequal in d-c generators.

When a-c generators are operated in parallel, however, only the loading may be unequal. Frequency (electrical speed) and voltage must both be equal. Where synchronizing force was required to equalize only the voltage between the d-c generators, these forces are required to equalize both voltage and speed (frequency) between two a-c generators. Therefore, on a

comparative basis, the transient synchronizing forces for a-c generators are much greater than for d-c generators. When a-c generators are of sufficient size, and are operating at unequal frequencies and terminal voltages, severe damage may result if they are suddenly connected to each other through a common bus. To avoid this, the generators must be synchronized as closely as possible before connecting them together. This is accomplished by connecting one generator to the bus (referred to as the bus generator), and then synchronizing the other, or incoming generator to it before closing the incoming generator's main power contactor. The generators are synchronized when the following conditions are set:

1. Equal terminal voltages. This is obtained by adjustment of the incoming generator's field strength.
2. Equal frequency. This is obtained by adjustment of the incoming generator's prime mover speed.
3. Phase voltages in proper phase relation. (Connecting phase voltages must reach peak values at the same instant.) The generators could have the same frequency, and still not be in step. That is, if the two generators have the same frequency, but one is lagging the other, the lagging generator remains a fixed number of degrees behind the leading generator, until it is accelerated slightly to catch up.
4. Phases connected in proper sequence. One pair of phases may be properly connected, while the other two pairs may be crossed. In this case, the phase sequence of one generator may be ACB, while the other is ABC.

Synchronizing A-C Generators

All of the foregoing conditions may be set by the following methods.

Equal voltages may be checked by using a voltmeter. The remaining conditions, equal frequency, phase relations, and phase sequence, are checked by using synchronizing lamps. There are a number of ways in which synchronizing lamps may be connected, but the most satisfactory arrangement is the 2-bright 1-dark method. This connective arrangement is shown in figure 6-17. Note that the lamps are connected directly between the incoming generator's output and the buses. In this way, the two a-c sources may be synchronized before the incoming generator's main power contactor is closed.

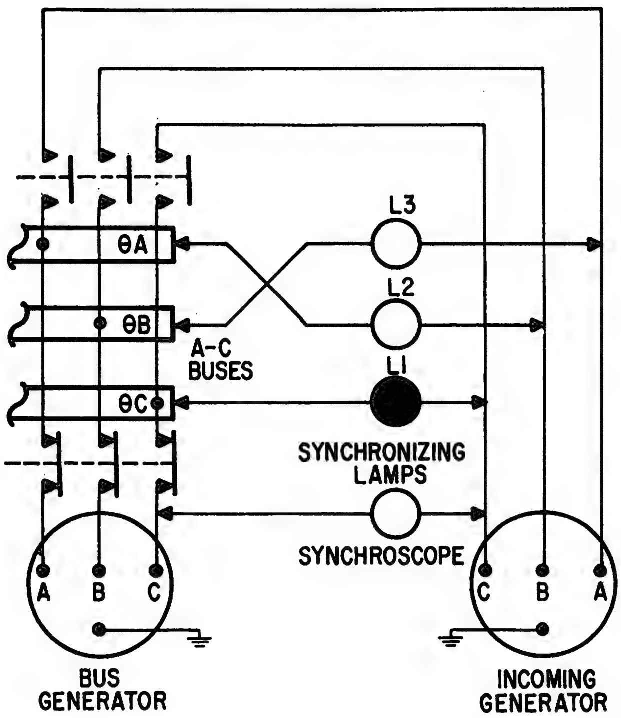

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Figure 6-17.—Synchronizing lamp connection for 2-bright 1-dark method.

Assume that the incoming generator is far out of synchronism, lagging. All three lamps appear to glow steadily, because the frequency of the voltage across them is the difference in the frequencies of the two generators, and thus is too high for individual alternations to be observed. As the lagging generator is accelerated, however, the lamp (differential) frequency decreases until their light flickers visibly. Their flickering has a rotating sequence, if connections are correct, and indicates which generator is faster.

At a point approaching synchronism, lamp L1 is dark because it is connected between like phases. That is, the 2-phase C voltages are so nearly synchronized that their differential voltage across L1 is insufficient to make it glow visibly. However, this differential is still of sufficient magnitude to damage the generators should they be connected at this time. The reason for cross-connecting L2 and L3 is now indicated. Under perfectly synchronized conditions, the phase voltages across L2 and L3 are both 120° apart, because of their cross-connection,

and both glow with equal brilliance. However, if the generators were not in complete synchronism, but only very near it, the small angular phase difference would add to the voltage of L2 or L3 (depending on phase sequence) and subtract from the other. This relatively small difference in voltage, undetectable in L1, would cause a visible difference in the brilliances of L2 and L3. Thus, by adjusting the incoming generator's frequency, and setting L2 and L3 so that no visible difference of brilliance exists, the generator frequencies and phase rotations may be synchronized very closely.

In addition to checking frequency, the lamps also indicate improper phase sequence, such as would occur if the generators were improperly connected. For instance, if the conductors were crossed at terminals A and B on either generator, L2 and L3 would then be connected between like phases, just as L1 is already connected. Consequently, all lamps would flicker in unison as synchronized frequency was approached, and all would finally darken simultaneously, indicating incorrect phase sequence.

If a conductor from terminal A or B were crossed with C at either generator, then all three lamps would be connected between unlike phases. As a result, they would all flicker in unison as synchronized frequency was approached, and all would finally glow with equal brilliance, which would also indicate incorrect phase sequence.

In addition to the foregoing, it is possible that the two generators have exactly the same frequency, as indicated by a stationary synchroscope rotor, be connected properly, and yet have the wrong lamp dark. Should this happen, however, it merely indicates that one generator is exactly 120° behind the other. This condition is easily corrected by slowing the incoming generator momentarily, until the proper lamp is dark and the other two are of equal brilliance.

When the lamps have been used to get the generators as nearly synchronized as is visibly possible, the synchroscope, being a highly frequency-sensitive instrument, may be used to make the final fine adjustment to the incoming generator's frequency.

After all the foregoing checks and adjustments are made, the incoming generator's main power contactor may be closed, with very little disturbance on the line. If the bus generator is supplying a load when the incoming generator is connected, the incoming generator should assume approximately one-half the load, provided the generators and their prime movers are of identical types and rating. The bus generator's voltage and frequency tend to rise at the loss of load, but the incoming generator's voltage and frequency tend to fall when it assumes part of the load. As a result, but voltage and frequency are unaffected. The only changes that take place occur in the prime mover governors and voltage regulators.

AUTOMATIC FREQUENCY CONTROL AND LOAD BALANCING

AUTOMATIC FREQUENCY CONTROL OF A-C GENERATORS

Until recent years, any demand for a constant-frequency a-c power supply in an aircraft was usually satisfied by one or more inverters. Constant-frequency delivered by an engine-driven generator was difficult to obtain, because of constant changes in the engine's speed. The problem of increased weight precluded for a time the use of a device to convert variable engine rpm into a fixed generator-drive rpm. However, as the power demanded from fixed-frequency systems increased, the size of the inverters also increased. This trend continued until the weight of the inverters, plus the extra weight required in their d-c power supplies, became as great as the combined weight of the a-c generators and their constant-speed drivers. Thus, constant-speed engine-driven a-c generators were made feasible, and came into use. Since the introduction of constant-speed engine-driver a-c generators, one of the AE's new duties has been to become familiar with the frequency controls of these systems.

Nonelectrical Frequency Control

In most instances, a-c generator frequency is controlled by a mechanical governor which controls the speed of the prime mover driving device. In these installations, electrical frequency sensing and correction is not used. Where compressed air turbines are used, jet engine driving power is utilized in the form of compressed air taken from the compressor section of the engine. A-c generator speed is then controlled by the amount of air passed through the turbine.

Another engine-powered and mechanically speed-regulated a-c generator drive is the type used on the A-4E aircraft. This assembly

consists of an engine-driven transmission and an integral lubricating system. The assembly's input rpm varies with engine speed. However, its output rpm is held within a narrow speed range by the assembly's speed change mechanism.

Though the foregoing types of drives are classed as constant-speed, they actually allow generator frequency to vary over an approximate 40-hertz range. One of the reasons that this comparatively wide frequency range is permissible is that none of the mechanically controlled systems are operated in parallel. Some large aircraft, including the A-3A, and EC-121 have more than one a-c generator, but their systems include no provisions for parallel operation. Instead, each generator supplies a separate bus with provisions for either generator to supply both buses should one generator fail.

Electrical Frequency Control

When an installation must provide for parallel operation of its a-c generators, at least two additional features must be included which are not found in mechanically-controlled systems. Frequency must be automatically controlled within a very narrow range, and a manual frequency control must also be provided. These two features enable the AE to obtain close synchronization of the generators prior to connecting them in parallel. To fulfill these requirements, electrical frequency controls are employed. These type controls are used because they are inherently more sensitive to frequency changes than mechanical controls. An electrical type system is also more easily controlled from a remote location by use of a servo loop.

The schematic in figure 6-18 represents such a system that is in current use.

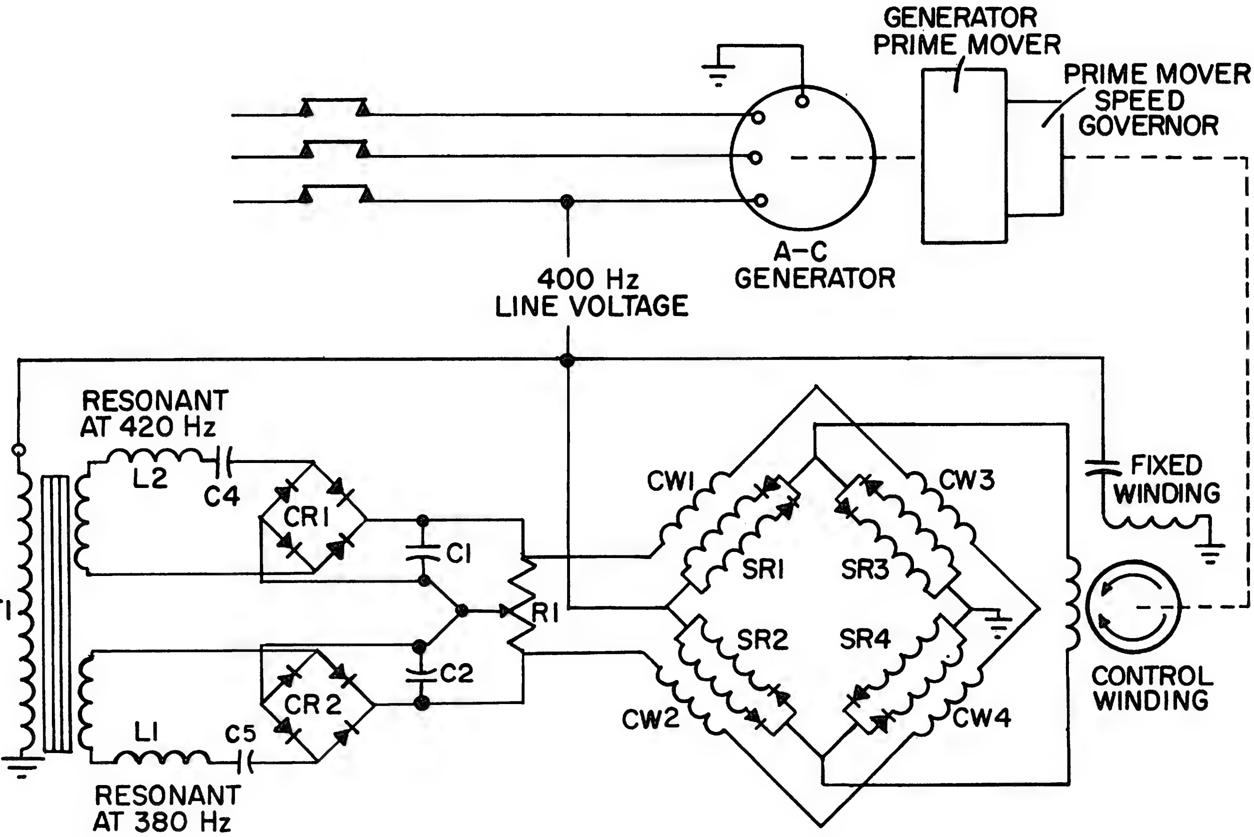

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Figure 6-18.—Electrical frequency sensing and control system.

The line voltage, whose frequency is to be regulated, is connected across the primary of a transformer T1 which has two secondary windings. Each secondary circuit consists of a series circuit comprised respectively of an inductance, capacitance, rectifier, and one half of potentiometer R1. The series combinations of L2 and C4, and L1 and C5 are each 20 hertz away from resonance when the line frequency is 400 hertz. Capacitors C1 and C2 filter the ripple output of rectifiers CR1 and CR2, so that a smooth d.c. flows inward from opposite ends of R1. The center tap of R1 is a common return for both rectifiers.

When the frequency is 400 hertz, the impedance of L1 and C5 is equal to that of L2 and C4, because both are being subjected to a frequency that is 20 hertz away from their resonant frequencies. Assume line frequency rises to 410 hertz. L2-C4 is now only 10 hertz per second off resonance, so its impedance decreases. However, L1-C5 is now 30 hertz off resonance and its impedance increases. As a result, a greater voltage appears across the upper half of R1 than across the lower half, and d.c. flows through the saturable reactor control coils CW1, CW3, CW4, and CW2. These coils are wound so that with a given direction of d.c. flow, their effect is to increase the inductance of the SR1 and SR4 load windings, while decreasing the inductance of the SR2 and SR3 load windings. Current is effectively cut off through SR1 and SR4, so that alternating current flows only through a series path comprised of SR2, the motor control winding, SR3, and ground. The resultant motor rotation is in a direction to lower the prime mover governor setting, and thus bring line frequency back down to 400 hertz.

If a drop, rather than rise, in line frequency initiates a control cycle, the control coil current is in an opposite direction. SR2 and SR3 are cut off, and alternating current flows in the series path of SR1, the motor control field, SR4, and ground. It is significant to note that for a given direction of control coil d.c., a given alteration of applied line voltage flows upward through the motor control winding. Had control coil d.c. been reversed, that same alternation would have flowed downward. Thus, the direction of the induction motor's field rotation, and consequently its shaft rotation, is controlled by the direction of the saturable reactor control winding current. The direction of the control winding current is in turn controlled by line frequency.

The system just described is more sensitive, and maintains closer frequency control than any mechanical control system in current use. Thus, it fulfills the requirement of close automatic frequency control. It also provides the required means of remote manual frequency control. Manual frequency adjustments are made simply by moving the wiper of R1 away from the center, in whatever direction frequency must be changed.

AUTOMATIC REACTIVE LOAD BALANCING

The system shown in figure 6-19 is designed to sense and correct an unbalanced reactive loading between two a-c generators.

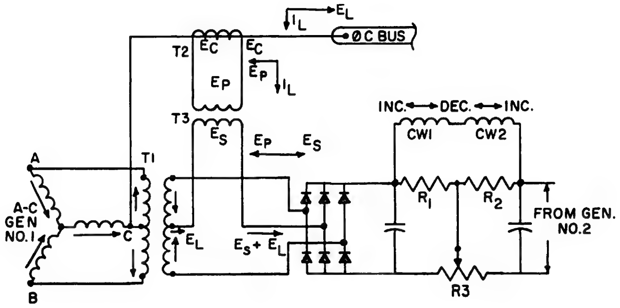

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Figure 6-19.—Reactive load balancing system.

Its basic operating concept is that the averaged d-c voltage across R1 is directly affected by the phase angle between the generator's line current and line voltage. This system is VARS-sensitive. That is, when line current I_L and line voltage E_L are in phase, the voltage across R1 is minimum. When line current and voltage are farthest out of phase, as shown in figure 6-19, voltage across R1 is maximum. This effect results from the timing of the outputs from two different transformers T1 and T3, both of which are referenced to a common power supply (phase C in fig. 6-19). The voltage reference is transformer T1, and the current reference is the current transformer T2. T3 is a coupling transformer.

The output of T1 is fixed in relation to line voltage, regardless of where line current lays in phase relation. The output of T2, however, swings with line current, always lagging it by approximately 90°, regardless of where line

oltage lays in phase relation. Thus, in figure -19, where I_L is assumed to be 90° out of hase with E_L, the output of T2 (E_c) and consequently the input of T3 (E_p) is 180° out of hase with the line voltage E_L. Since T3 is a oltage transformer, its output E_S is shifted 180° rom its input Ep. Through the foregoing steps, he original current-reference output E_C is hifted so that it comes out directly in phase with he voltage-reference output E_L. Their combined oltage E_SE_L can thus be seen to cause the reatest average rectifier d-c output across R1 when line current and voltage are farthest out f phase.

When line current swings more in phase with ine voltage, this swing is reflected through the ame sequence of steps so that E_S is moved out f phase with E_L, and the average d-c voltage s reduced.

Figure 6-19 shows the output of two such networks connected in electrical opposition to one another. They are connected in parallel with the control windings (CW1 and CW2) of two a-c generator voltage regulators. The voltage across R1 reflects the VARS being supplied by generator No. 1, and the voltage across R2 likewise reflects the VARS being supplied by generator No. 2. When the generators have equal line phase angles (regardless of angle magnitude), the current through CW1 and CW2 is zero. f the line phase angle of one generator becomes greater than that of the other, the result is unequal voltages across R1 and R2. This produces a current through the voltage regulator windings CW1 and CW2. For a given direction of current, the field excitation of one generator is increased, while that of the other is decreased. The reactive load of each generator is thus shifted until the two are equal, at which time the current through CW1 and CW2 is again at zero. The reactive load may also be shifted manually by moving potentiometer R3.

WATT LOAD BALANCING

The system shown in figure 6-20 is designed to sense and correct an unbalance of watt load between two a-c generators.

The system is watt-sensitive because the outputs of CR1 and CR2 across their respective halves of R1 are equal only when line current and voltage are in phase. This characteristic is achieved as follows. In the voltage reference transformer T1, the secondary voltage E_{S1} and E_{S2} always act in the same direction, and are always of the same magnitude. If the current-transformer T2 and its output E_{R1} were not in the circuit, the voltage and current in the primary windings of T3 and T4 would be equal. However, when the current-following voltage E_{R1} is connected as shown, its two components e1 and e2 act in opposite directions through the secondary windings of T1. E_{S1} is boosted, while E_{S2} is bucked. As a result, the primary voltage of T3 is increased, and that of T4 is decreased. This unbalance is reflected in their secondaries, and in their rectified d-c outputs.

Though T2's output E_{R1} is constant, its effect on the system is variable as a function of its timing. E_{R1} is always at 90° to line current, because T2 is a current transformer. Therefore, the timing, or phase relation, of E_{R1} to line voltage is determined by the phase relation of line voltage and line current. In the network, line voltage is referenced and represented by E_{S1} and E_{S2}. In the vector diagrams, it can be seen that when line current I_L and line voltage E_L are in phase, the voltages E_{R1} and E_L are 90° apart. When E_L is reduced to its components E_{S2} and E_{S1}, and E_{R1} is reduced to its components e1 and e2, it can be seen that when they are 90° apart, there is no buck and boost action. However, when line current swings out of phase with line voltage, by 45° for instance, e1 is moved more in phase with E_{S1} while e2 is moved farther out of phase with E_{S2}. Thus the greater the line phase angle, the more pronounced is the imbalance in d-c output.

When two such networks are interconnected as in figure 6-20, unequal generator watt loads, indicated by unequal line phase angles, result in unequal d-c voltages across R1 and R2. The resulting current flow through the saturable reactor control windings CW1 and CW2 causes the watt loads to be balanced by causing the prime mover governor settings to be moved. Manual load balancing may be accomplished by moving potentiometer R1 or R2.

CONSTANT-SPEED DRIVE ASSEMBLY

A constant-speed drive (CSD) assembly is a hydromechanical device consisting of one complete assembly mounted on the engine or in the aircraft to maintain the a-c generator at a constant speed. The purpose of the assembly is to transfer and convert variable-speed rotation of the aircraft engine to a constant-speed rotation required to drive the aircraft generator.

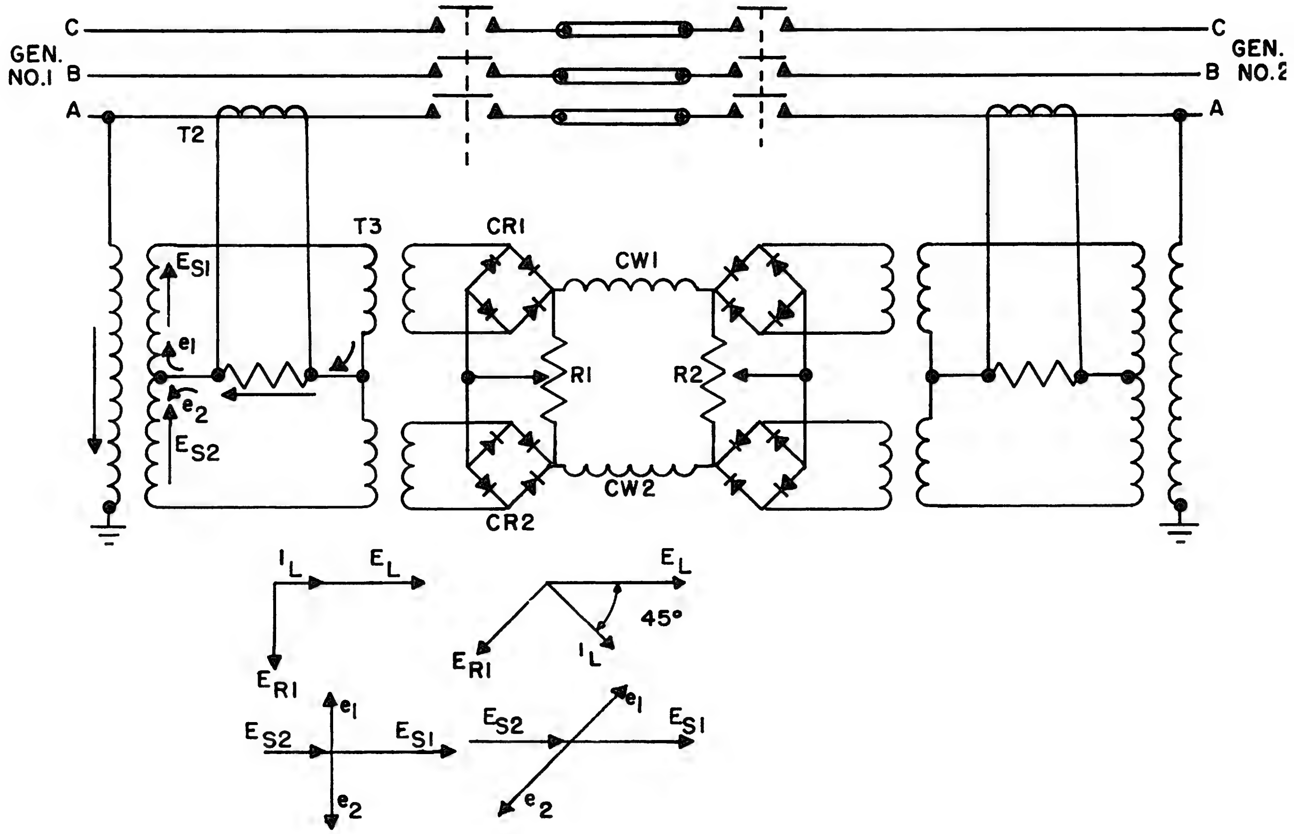

Figure 6-20.—Automatic watt load balancing system.

The constant-speed drive consists of a variable-displacement hydraulic pump, whose volume of oil output can be controlled, a constant-displacement hydraulic motor which turns faster or slower as the pump forces more or less oil into it, and a governing system which controls the rate of flow from the pump and thereby controls the speed of the motor. The rate of flow from the pump is determined by the position of the pump wobbler assembly. The position of the pump wobbler assembly, in turn, is controlled by the basic governor. In addition to the basic governor, a limit governor is provided for protection of the generator from overspeed should the constant-speed assembly become inoperative. There are several other components in the CSD which are necessary for self-regulating constant-speed operation. Among these components are three output-driven gear pumps: the charge pump, the replenishing pump, and the scavenge pump. These pumps, the limit governor, and the basic governor are driven by a gear on the constant-speed output shaft.

The pump wobbler and the pump section of the cylinder block assembly form the variable displacement pump in the CSD. A simplified pump-motor functional diagram is shown in figure 6-21.

The pump wobbler consists of an outer stationary shell and an inner race. The inner race is separated from the wobbler shell by bearing rollers and is free to turn with the pump pistons, which are in contact with the race at all times during operation. Two control pistons on opposite sides of the pump wobbler in the CSD housing move the wobbler sideways to vary the output of the pump.

The CSD functions in three different phases of operation. They are the overdrive phase, straight-through phase, and the underdrive phase.

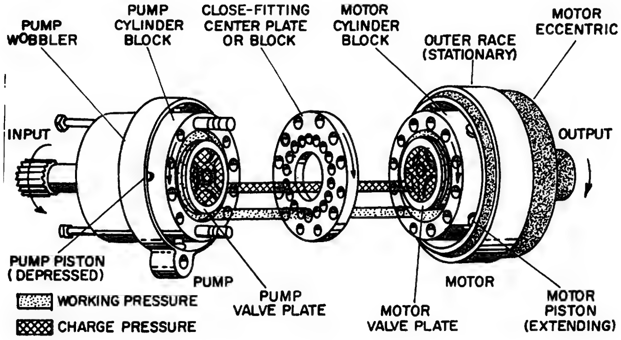

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Figure 6-21.—Simplified pump-motor functional diagram.

When the input rpm from the aircraft engine is less than the output rpm required for the generator, the CSD must make up the difference in rpm. This is accomplished by the pump wobbler system, in response to a governor signal, causing the pump to supply more oil to the motor. The difference between the input and output rpm depends upon the quantity of oil pumped which in turn is regulated by the wobbler pump. Anytime the motor wobbler (output) is rotating faster than the cylinder block assembly (input) the CSD is in overdrive.

When the input rpm exactly equals the required output rpm, the rotary motion is transmitted through the CSD without gain or loss of hydraulic action. The pump wobbler would, theoretically, be positioned through the action of the governor to be concentric with the cylinder block assembly. In this condition, the pump would neither pump oil to the motor nor accept oil from the motor. The motor pistons would be locked in position against the motor wobbler, forcing the wobbler to rotate at the same speed as the cylinder block assembly. Since the drive starts in underdrive and operates normally in overdrive, this straight through condition is only temporary. If the input rpm from the aircraft engine exceeds the output rpm required for the generator, the CSD must act to subtract from the input rotation. This is accomplished by moving the pump wobbler in response to the governor signal. The pump-motor action for underdrive is the reverse of the action required for overdrive. In the underdrive phase, the pump can be considered as performing a negative pumping action. The generator load opposes the driving force of the CSD so it tends to slow down the wobbler at all times. The cylinder block assembly then rotates faster than the motor wobbler, the excess input torque is dissipated in the reverse pumping action to the charge oil system. Whenever the motor wobbler is rotating slower than the cylinder block assembly, the CSD is in underdrive. When the engine overspeeds or if the basic governor should fail, the CSD goes into underdrive to protect the generator from overspeed.

An underspeed pressure switch is mounted in the governor oil lines. The pressure switch functions to break the electrical circuit of the a-c control system thus protecting the system during an underspeed condition.

Some CSD's utilize aircraft engine oil from the engine lubricating system for a hydraulic medium. In this case, the CSD also functions as a pump for supplying the generator with engine oil for cooling. The cooling capabilities of oil, being much greater than air, enables the generator to be constructed much smaller and more compact than a similar rated air-cooled generator.

CONSTANT-SPEED DRIVE/STARTER

The constant-speed drive/starter (CSD/S) unit is shown in figure 6-22. This new system provides both pneumatic starting for the engine and a constant-speed drive for the generator. The CSD/S can be operated in any of the following modes: Engine starter, constant-speed drive, or air turbine motor. Each of these modes is discussed in the following paragraphs.

Constant-Speed Drive

Figure 6-23 is a cutaway view of the constant-speed drive transmission. When it is operated in this mode, the engine input shaft drives the planet gear carrier counterclockwise. A planet gear, free to rotate around its shaft, is mounted on the planet gear carrier. The planet gear meshes with the generator drive sun gear and ring gear. The generator, connected to the generator drive sun gear, resists rotation. When the planet gear carrier is turned by the engine drive shaft, the planet gear spins on its shaft.

When the CSD/S unit is used as a starter, the ring gear is locked to the housing by a starting brake. This is shown in figure 6-24.

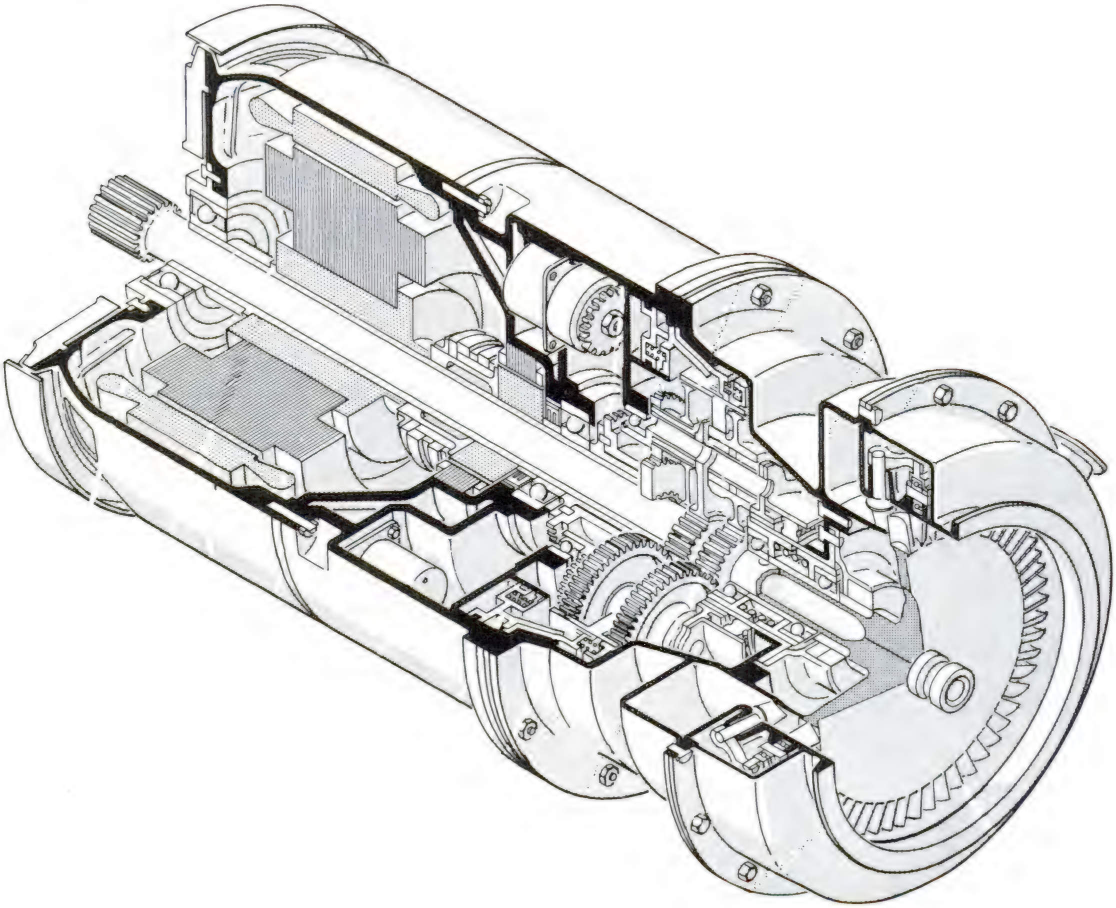

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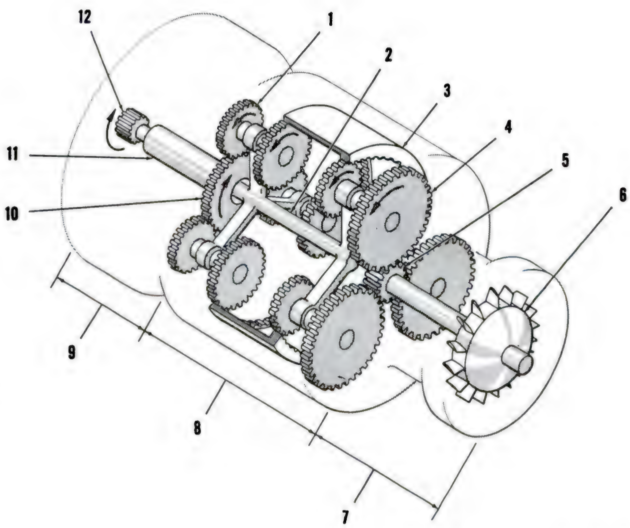
Figure 6-22.—CSD/S unit cutaway.

Compressed air from an operating engine or an external pneumatic cart drives the turbine, rotating the turbine sun gear. The turbine planet gear walks around the stationary ring gear, pulling the planet carrier with it and turning the engine drive shaft. When the engine has reached a speed sufficient to run itself, the CSD/S unit control system releases the ring gear. The CSD/S unit now begins to function as a constant-speed drive, turning the ring gear clockwise. The generator is not turned as long as the ring gear is free to rotate.

If the ring gear is prevented from turning by some means, the planet gear walks around the inside of the ring gear, and forces the generator drive sun gear to turn at a very high speed. To make the generator turn at the proper rpm, the ring gear must be allowed to turn, but not at its free speed. Both the planet gear carrier and the ring gear turn in the same direction, but at different speeds. Thus, it is the relative speed of the ring gear and the planet gear carrier which governs how fast the generator turns. If the engine, turning the planetary gear carrier, speeds up and the ring gear does not, the planet gear walks around the ring gear faster, overspeeding the generator. The ring gear is then made to rotate faster to restore the generator to its rated speed. If the engine slows, the ring gear is also made to slow more to keep the generator speed normal. The ring gear speed changes in direct proportion to the engine speed.

Keeping the ring gear from rotating freely requires power; this power is supplied by the turbine. The turbine planet gear is free to



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1. Planet gear carrier.
2. General compound planet gear.
3. Ring gear.
4. Turbine compound planet gear.
5. Turbine sun gear.
6. Starting turbine.
7. Turbine.
8. Transmission.
9. Generator.
10. Generator drive gear.
11. Generator drive shaft.
12. Engine input drive shaft.

Figure 6-23.—CSD/S transmission.

rotate the planet gear carrier. It meshes with the turbine sun gear and the ring gear. Rotation of the turbine makes the ring gear turn in opposite direction to that of the planet gear carrier. The generator planet gear tends to turn the ring gear fast and in the same direction as the planet gear carrier turns; the generator does not turn under this condition. By turning the turbine, the forward speed of the ring gear is reduced, forcing the generator planet gear to rotate the generator as described previously. The faster the turbine turns, the slower the ring gear tends to turn compared with the planet gear carrier.

There are two conditions which require adjustment of the power from the turbine—a change in engine speed and a change in electrical load. If the speed drops, the turbine must slow the ring gear more. This is accomplished by allowing more air to flow through the turbine, causing it to turn faster, decreasing the differential speed between the ring gear and planet gear carrier. If a greater load is placed on the generator, more power is required to hold the ring gear speed steady; again, more air is directed through the turbine, causing it to produce a greater torque at the same speed. Airflow through the turbine is controlled by varying the opening of the nozzle which surrounds the turbine wheel.

Air Turbine Motor

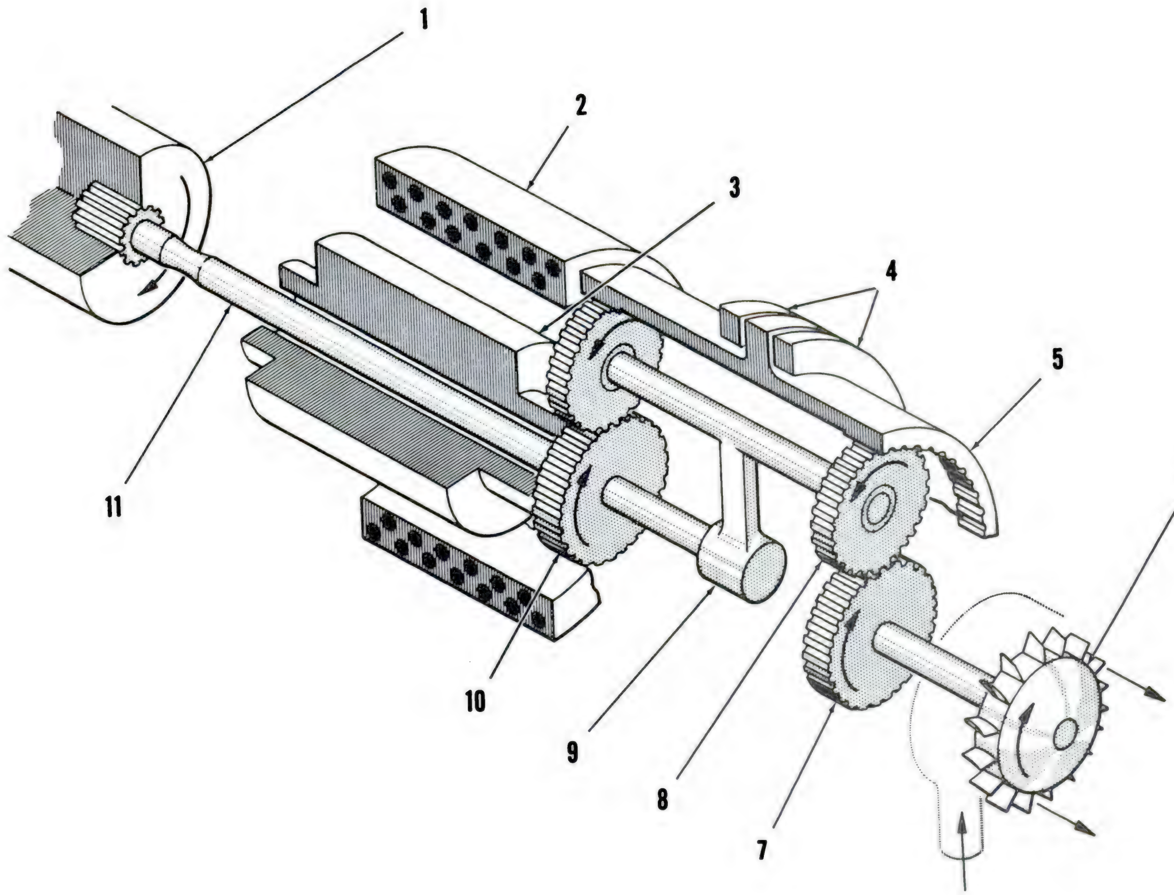
In this mode of operation the turbine supplies power through the differential transmission to the generator. Turbine air is furnished from an operating engine or an external pneumatic cart.

The generator speed is controlled by varying the opening of the turbine nozzles. Should an engine to which the CSD/S unit is attached become inoperative during flight, its CSD/S will assume this mode of operation, provided the turbine is supplied bleed air from an operating engine. This mode of operation is also used when the aircraft is on the deck. When the CSD/S is operated as an air turbine motor, the air turbine drives the ring gear counterclockwise, rotating the output gears and generator drive sun gear. The planet carrier and engine drive shaft are prevented from turning counterclockwise by the spray-clutch assembly. The control system keeps the generator at its normal speed by regulating airflow to the turbine.

SPLIT BUS OPERATION OF A-C GENERATORS

Before two a-c generators can be placed in parallel operation, they must have (1) the same phase rotation, (2) the same speed, (3) their voltages must be equal, and (4) they must be in phase or very nearly so. Until they are placed in parallel operation, each generator supplies a separate bus, a condition that is sometimes referred to as "split bus."

On the other hand, when two a-c generators are operating in parallel, if one generator can not maintain the conditions required for parallel operation, the system must be returned to split bus operation. If the generator fault is only minor, the generators will continue to operate split bus until the fault is corrected. If the fault is severe, the generator at fault is removed from its bus; at which time, the bus is



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1. Engine pad.
2. Generator stator.
3. Generator rotor (field).
4. Cone clutch (ring gear brake).
5. Ring gear.
6. Turbine.
7. Turbine sun gear.
8. Turbine planet gear.
9. Planet gear carrier.
10. Generator drive sun gear.
11. Engine drive shaft.

Figure 6-24.—Starter unit operation.

connected to the bus of the remaining good generator.

Purpose for Operating Split Bus

Operating a-c generators in parallel is, of course, preferred, but unlike motor driven generators (inverters), it is difficult to achieve and even more difficult to maintain for extended periods of time. The automatic paralleling system is quite complex—considerably more complex than the power generating portion of the system—and its rate of failure is high, which often expends many maintenance manhours. In such cases it is more advantageous to operate the generators in split bus.

Conditions for Split Bus Operation

The main consideration for a-c power generating system which is to be operated in split bus is that the bus and load of each

generator be isolated from each other. If this is not done, the generators will be tied to each other through their loads, and thus furnish paths for circulating currents between the generators. In most cases, these circulating currents will have little affect on the operation of the power generating system itself; however, they can create serious problems in those systems that are sensitive to frequency and phase variations.

A-C VOLTAGE REGULATORS

STATIC REGULATORS

Static a-c voltage regulators are used widely in naval aircraft. The static regulator has no moving parts in its entire regulating mechanism (except for exciter control relays). The two types of static regulators most commonly in use are the magnetic amplifier type and the transistorized type.

A new type of static regulator currently in use takes advantage of the design features of magnetic amplifier and transistor principles in its operation. This type of regulator is discussed in the following paragraphs.

The static voltage regulator explained in this section consists of the following circuits: highest-phase takeover (HPT); Zener diode reference; transistor preamplifier; 3-phase, half-wave, magnetic amplifier; and stabilizing circuits. These circuits are discussed briefly.

PRINCIPLES OF OPERATION

Highest-Phase Takeover

The HPT sensing circuit utilizes highest-phase takeover voltage sensing. It consists of autotransformers, rectifiers, an inductor, and a capacitor. The voltage regulator functions to maintain a constant voltage across the capacitor.

Zener Diode Reference

The Zener diode reference circuit consists of two diodes and a resistor. The voltage across the Zener diodes remains almost constant regardless of the voltage regulator input voltage. The resistor absorbs the line voltage variations.

Transistor Preamplifier

The transistor preamplifier consists of two transistors and two windings of a magnetic amplifier. An inductor and a capacitor form a ripple filter to the input base of one transistor. Two resistors are used as gain-stabilizing resistors in the transistor emitter circuit to stabilize gain against temperature changes. Rectifiers are used to prevent transistor breakdown by limiting base-to-emitter voltages.

Three-Phase, Half-Wave, Magnetic Amplifier

The 3-phase, half-wave magnetic amplifier consists of three windings. Resistors insure that each amplifier gate winding delivers an equal share of the magnetic amplifier output current. A capacitor is used as a radio noise filter, while a resistor is used as a current limiter. The input to the 3-phase, half-wave magnetic amplifier is supplied from the 3-phase line voltage. The output from the magnetic amplifier controls regulator output. This output is fed to the static exciter.

Stabilizing Circuits

The stabilizing circuit consists of a lead network (comprised of a capacitor and voltage divider) and a lead-lag network (a capacitor, resistor, transistor, and a filter capacitor). The stabilizing circuit permits fast regulator response with good stability.

Theory of Operation

The static voltage regulator (transistor/magnetic amplifier type) supplies a control signal to the static exciter that regulates generator output. (See fig. 6-25.) This control signal is developed in the following manner. The output of autotransformers T101, T102, and T103 of rectifiers CR104, CR105 and CR106, and of inductor L104, is proportional to the average of the three line-to-neutral voltages. The output of autotransformers T101, T102, and T103, as rectified by CR101, CR102, and CR103, represents the peak of each line-to-neutral voltage. During normal operation (with balanced or moderately unbalanced loads) the peaks of the outputs of CR101, CR102, and CR103 will be slightly under the voltage from the output side of L104 to ground. Hence,

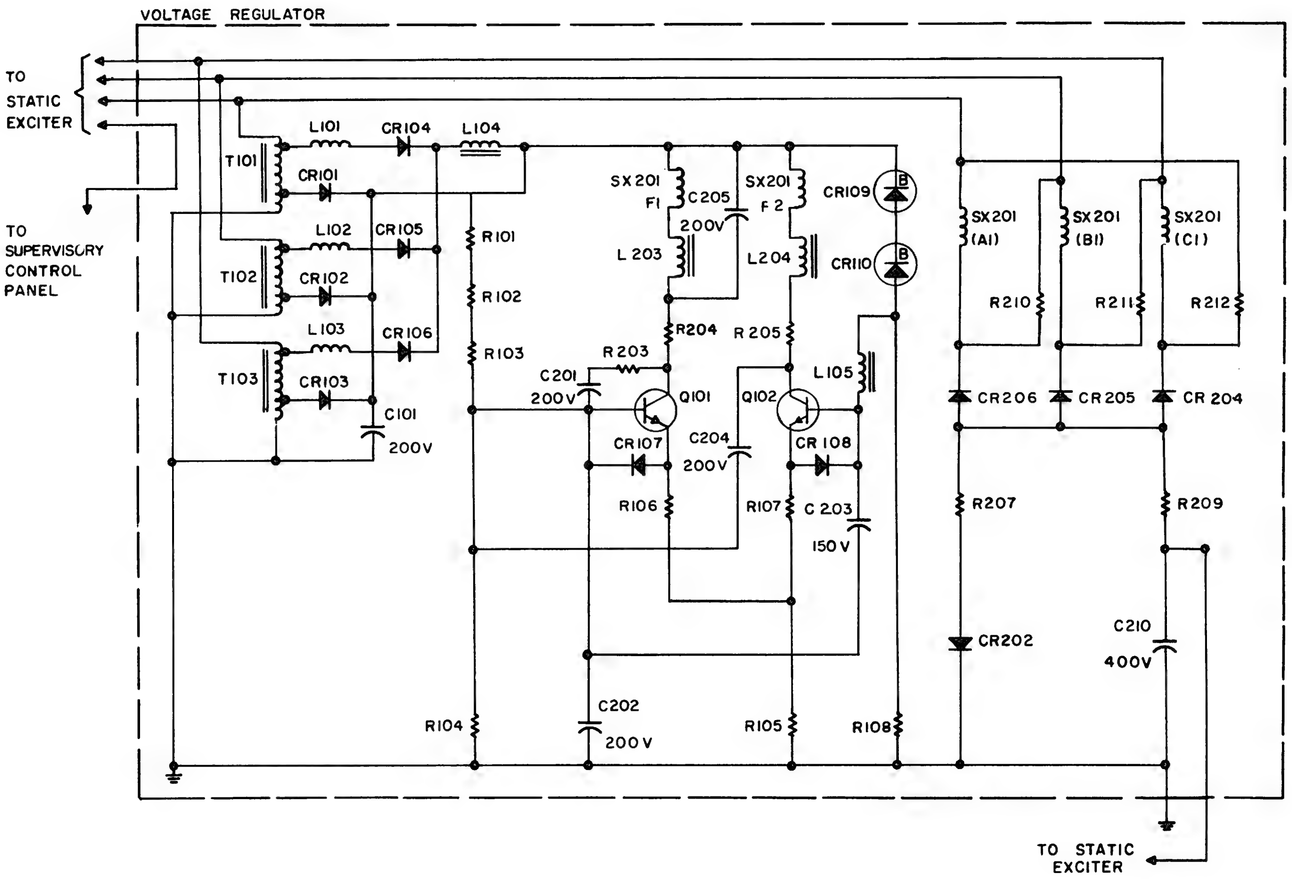

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Figure 6-25.—Transistor/magnetic amplifier voltage regulator schematic.

C101 will be charged up to a level representing this average value, and the regulator will regulate the average value of line voltage. During operation with a large unbalanced load, the voltage of one of the lightly loaded phases will tend to rise considerably, thus causing one of the peak voltages from CR101, CR102, or CR103 to exceed the average voltage output of L104. Capacitor C101 will then be charged up to this peak value and the regulator will regulate and tend to limit the rise of this voltage. This circuit is so designed that the highest-phase takeover is gradual and the point of takeover is not sharply defined. (Note that inductors L101, L102, and L103 are radio noise filters and do not form an essential part of the HPT sensing circuit.)

The actual voltage being regulated is the voltage between R104 and ground, in the voltage divider (R101, R102, R103, and R104) that is connected across capacitor C101. This voltage is compared with the voltage to ground to form an error signal. This error signal is then fed to the transistor preamplifier and from there to the magnetic amplifier SX201 to control the regulator output. Resistors R102 and R103 are used to adjust the line voltage to the desired value. The Zener diodes CR109 and CR110 form the reference voltage. The voltage drop across them is almost constant regardless of operating conditions, once the system voltage is built up. Resistor R108 limits the current through these diodes and absorbs the line voltage variations.

It should be noted that both the voltage divider circuit (R101 to R104) and the voltage reference circuit (CR109 and CR110) are both connected to the HPT output. Thus, the same d-c voltage will

appear across both circuits. Should the 3-phase line voltage rise approximately 2 volts line-to-ground, the voltage rise will be approximately 2 volts d.c. Because the voltage drop across the Zener diodes stays constant, the potential with respect to ground will rise only by the ratio of the value of R104 to the sum of the values of R101, R102, R103, and R104. This represents a rise of approximately 1.68 volts. An error signal of 0.32 volts (2 minus 1.68) is then applied across the bases of transistors Q101 and Q102 in the transistor preamplifier. The transistor preamplifier is so connected that when the base of Q101 is more negative than the base of Q102 (as it is when the line voltage rises), it will feed less current to magnetic amplifier SX201 and control winding F1. At the same time Q102 will feed more current through control winding F2. This difference in control winding signals causes the output of the magnetic amplifier to increase, thereby returning the line voltage to normal. Conversely, a decrease in line voltage will tend to reduce the potential. Thus, the base of Q101 will be at a higher potential than the base of Q102 and a different signal will be supplied to the magnetic amplifier causing it to decrease its output. This, in turn, will tend to raise the line voltage.

There are a number of other components associated with the transistor preamplifier. They are: inductor L105 and capacitor C203, which form a ripple filter on the input base of Q102; resistors R106 and R107, which are gain-stabilizing resistors placed in the transistor emitters to stabilize transistor gain over the equipment's operating temperature range; and rectifiers CR107 and CR108, which prevent transistor breakdown by limiting base-to-emitter voltages.

The magnetic amplifier used to control the regulator output is a 3-phase, half-wave type, and its input is supplied from 3-phase line voltage. Rectifiers CR204, CR205, and CR206 are so connected that current is fed to the amplifier gate windings A1, B1, and C1 during the negative half of the cycle. By contrast, current flows in the HPT circuit only during the positive half of each cycle. During the portion of each half cycle in which the amplifier gate winding fires, a heavy pulse of current will flow through the regulator sensing leads. If the sensing lead impendance is high, this current will cause an instantaneous drop in the voltage at the regulator end of the sensing leads. If the magnetic amplifier was connected so that current flowed to the amplifier during the positive half of each cycle, this voltage drop would affect the voltage seen by the HPT circuit and cause erroneous regulation. However, the HPT circuit will not see voltage drops present during the negative half cycle.

Other components associated with the magnetic amplifier are: resistors R210, R211, and R212, which insures that each magnetic amplifier gate winding delivers an equal share of the magnetic amplifier output current; radio noise capacitor C210; current-limiting resistor R209; rectifier CR202; and resistor R207, which limits peak current through CR202.

VOLTAGE CONTROL OF INVERTERS

Electronic Inverter Voltage Regulators

There are a number of electronically regulated inverters, and detailed information for each may be found in the Overhaul Instruction Manual for the particular unit. The type of voltage regulator discussed here is used only as a typical example, though it closely resembles the type used in the Holtzer-Cabot D-139 inverter.

The main advantage of a purely electronic inverter voltage regulator is that it contains no moving parts, such as those in the carbon-pile regulator. A regulator of this type is shown in figure 6-26.

Its operation is as follows. One phase of the inverter voltage to be regulated is applied to transformer T3. The secondary output is half-wave rectified, so that the top secondary winding conducts through V1A on one half-cycle, and the bottom winding conducts through V1B on the other half-cycle. Filter networks F1 and F2 produce d.c. across both VR1 and resistor R2. Any change in inverter a-c voltage is translated into a change in the average d-c voltage output of the filter networks. Any variation in the output of F1 appears across R2. However, since VR1 maintains a constant voltage drop across itself, the equal and simultaneous variations in the output of F2 must appear across R1. The differential of the voltages across R2 and VR1 is applied across the grid and cathode of V2. In a condition where inverter voltage is normal, the upper end of R2 is less positive than the lower

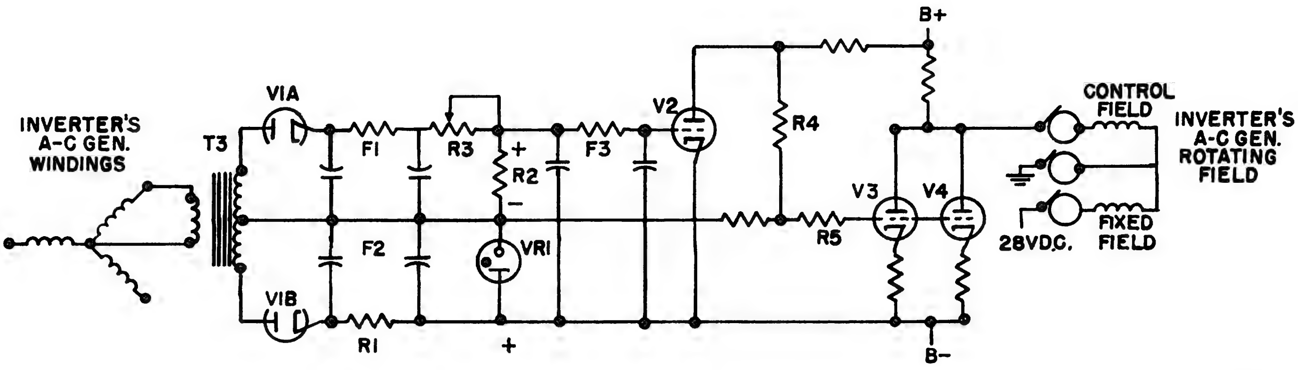

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Figure 6-26.—Electronic inverter voltage regulator.

end of VR1. Consequently, the cathode sees the grid as being negative, because the cathode is more positive than the grid. The magnitude of the relatively negative grid voltage is such that V2 is operated class A. In this way, grid voltage, and thus tube conduction, can follow any variation in inverter voltage either above or below its normal level. Filter network F3 removes any ripple from the V2 grid voltage, but does not affect its magnitude. R3 is the voltage adjusting rheostat.

The voltage of VR1 is also applied across the grid and cathode of the parallel tubes V3 and V4. This negative biasing is such that V3 and V4 are also operated class A. Variations in the conduction and plate voltage of V2 act through R4 and R5 to affect the conduction of V3 and V4. The steady-state B+ current flowing through the control field is varied as the plate voltage of V3 and V4 is varied. In summation, it can be seen that a decrease in the inverter's a-c voltage causes a decrease in the input voltage to T3. The result is an increase in the output through the control field, raising the output a-c voltage back to its original value.

Another type of voltage regulator is shown in figure 6-27. This type is used in certain Leland inverters. It is not a purely electronic regulator, because a carbon pile is employed to furnish the necessary current variations through the inverter's a-c generator field. Only the voltage error sensing and amplification are done electronically in this regulator.

The entire voltage of each alternation through secondary winding S1 is rectified by V1 and V2 and appears across V3 and R2. Secondary S2 is the voltage-sensor pickup, and heats the filament of V3. S2's output, governed by line a-c voltage, thus varies the filament temperature of V3 in accordance with line voltage. Variations of its filament temperature causes variations in the cathode electron emission, and consequently the conduction of V3. Therefore, the conduction of direct current and the plate voltage of V3 is controlled through S2 by the line voltage. Capacitor C1 stabilizes the regulator's operation by smoothing out changes of voltage across V3.

With a rise in line voltage, V3's conduction increases, and its plate becomes less positive. The grid of V4 must also become less positive, and therefore the conduction of V4 decreases. The resulting decrease of control coil current permits decompression and thus causes increased resistance in the carbon pile. When the generator field current is thus decreased, line voltage decreases to its original value. It should be noted that when this type regulator is used the carbon-pile resistance variation in relation to changes of control coil current is the reverse of what it is usually found to be. That is, in most carbon-pile regulators, a decrease of control coil current would cause a compression and decreased resistance in its carbon pile. Where coil magnetomotive force pulls an iron slug away from the stack in most regulators, the same magnetomotive force when applied in the Leland inverter presses an iron slug against the carbon stack. R1 is used for voltage adjustment.

A third type of voltage regulator appears in figure 6-28. This regulator is similar to the ones used on certain Jack and Heintz inverters. It is essentially a rectifier/carbon-pile regulator

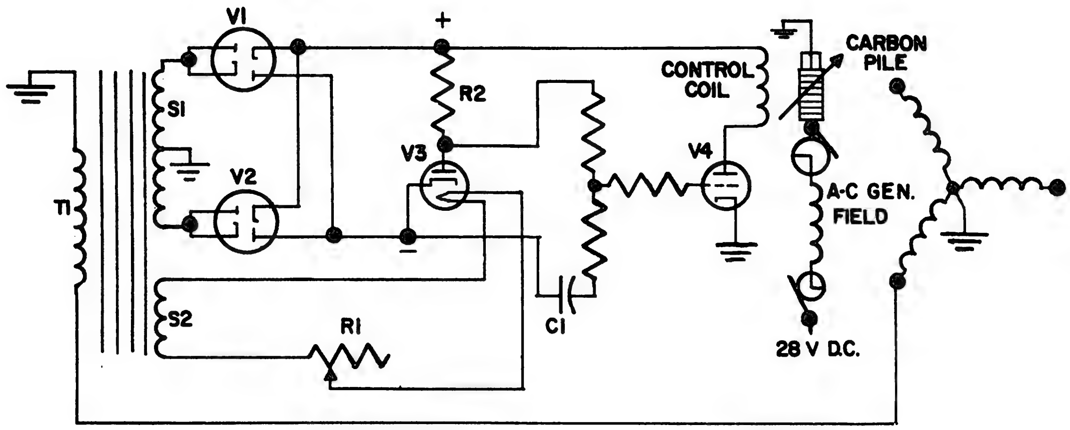

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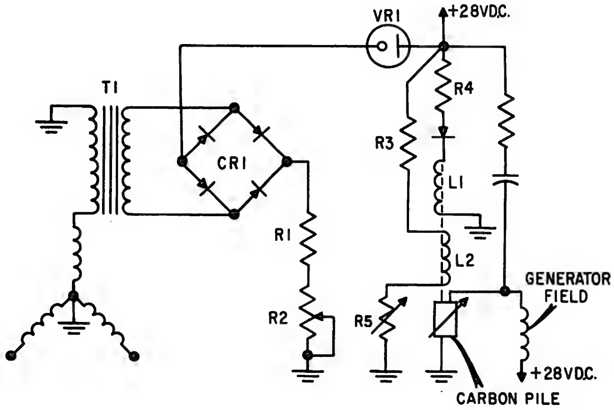
Figure 6-27.—Electronic carbon-pile regulator.



AE.527
Figure 6-28.—Semielectric inverter voltage regulator.

and is discussed because it employs at least one electronic part. Its operation is as follows.

Voltage regulation is obtained by controlling the amount of direct current (excitation) flowing through the generator field. This is accomplished by sensing the output voltage and automatically varying the generator field circuit resistance in response to output voltage changes, thus supplying enough excitation current to maintain the a-c output voltage at its preset value. The carbon pile is connected in series with the generator field; the operation coils provide magnetic action in such a direction as to increase or decrease the pressure on the carbon pile, thus changing the carbon-pile resistance and increasing or decreasing the generator field current as required.

To accomplish this, the main carbon-pile operating coil (LI) is supplied a fixed current from the main d-c supply through a resistor and a diode. In direct opposition to the fixed current (bucking action), the other operating coil (L2) is supplied a current proportional to the a-c output voltage; the a-c output voltage is supplied to an isolation transformer whose output, in turn, is rectified to d.c. and applied to the voltage regulating tube, resistor (R3), operating coil (L2), and voltage adjustment potentiometer (R5) all connected in series. The voltage regulating tube is designed to prevent current flow until the applied d-c voltage (proportional to a-c output voltage) has reached a predetermined value. As the inverter is started, the current flow through the main coil (L1) is from the main d-c supply only; this provides for rapid voltage buildup since the fixed current in the operating coil results in maximum force on the carbon pile (minimum resistance) and, therefore, maximum generator field current.

When the a-c output voltage increases to the point where the voltage regulating tube fires, bucking current is supplied to the operating coil (L2) resulting in a decrease in magnetic force acting on the carbon pile (increased resistance). The generator field current decreases until a stabilized condition is reached where the generator field current is just sufficient to maintain the correct output voltage.

Occurrence of conditions which tend to decrease the a-c output voltage (decrease in input voltage or increase in load), cause the current through the voltage regulating tube to decrease. This results in a greater magnetic force acting on the carbon pile and consequently an increase of generator field current. With conditions tending to increase the a-c output voltage, the action is reversed and field current is decreased. Voltage adjustment is made with R2 and R5.

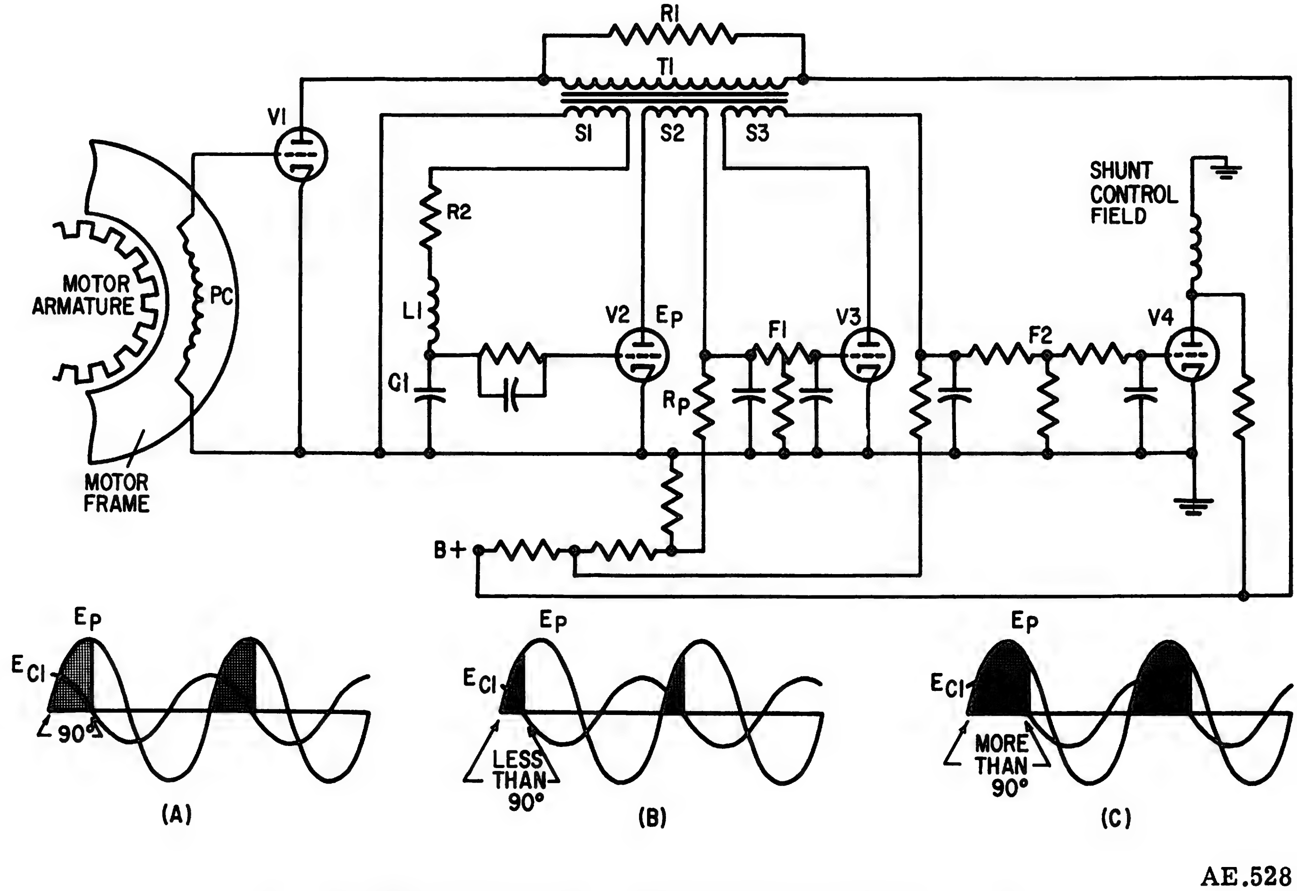
FREQUENCY CONTROL OF INVERTERS

Electronic Frequency Control

Figure 6-29 is a simplified drawing of the all-electronic frequency regulator used on the Holtzer-Cabot D-139 inverter.

Flux ripple in the motor frame, caused by the rotating motor armature, includes a small alternating voltage in the pickup coil (PC). The frequency of this a-c voltage is proportional to the motor armature speed, and thus varies with the frequency of the main a-c output. Consequently, it can be used as an indication of output frequency. When an a-c signal from the pickup coil is applied to the grid of V1, it is amplified, and a rippling d.c. flows through the primary of T1, with a frequency the same as that coming from PC. An a-c voltage, still of the same frequency, is then induced into secondaries S1, S2, and S3.

When the main a-c voltage is at the proper frequency, the PC frequency in S1 is the resonant frequency of the series combination of R2, L1, and C1. Under this condition, the voltage across C1 lags the voltage of S1 by 90°, but leads the voltage of S2, as felt on the plate of V2, by 90°. Thus, V2 is operated as a grid-controlled rectifier. In the sine wave diagram in figure 6-29 (A), it can be seen that when the



AE.528

Figure 6-29.—All-electronic inverter frequency regulator.

voltage across C1 leads the voltage across V2 (Ep) by exactly 90°, tube V2 conducts for exactly one-half of each positive alternation of its plate voltage. The half-cycle of V2's plate voltage (Ep) during which conduction takes place is the shaded area shown in (A). Note that conduction takes place only when both sine waves lie on the positive side of their respective zero values.

If the inverter speeds up, the frequency across R2-L1-C1 goes above resonance for that circuit, and E_{C1} leads E_P by less than 90°. The result, decreased conduction through V2 is shown in part (B). If the inverter slows down, the frequency across R2-L1-C1 goes below resonance, and E_{C1} leads E_P by more than 90°. The result, increased conduction through V2, is shown in part (C).

The pulsating output of V3 across its plate resistor R_p is filtered through network F1 and appears on the grid of V2 as a d-c voltage. This d-c voltage is the average of the pulsating voltage on the plate of V2. The magnitude of this d-c voltage on its grid affects the average conduction of V3 in the same way as the timing of an a-c voltage on its grid affected the conduction of V2. The output of V3 is filtered across network F2, and appears as a d-c voltage on the grid of V4. Thus, through the foregoing sequence, any change of inverter frequency results in a change of grid voltage at V4. Variations in the grid voltage of V4 causes variations in its conduction and plate voltage. These variations of V4's plate voltage cause changes in the d.c. through the inverter motor's speed controlling shunt field and are in a direction to oppose whatever changes in motor speed initiated the regulating cycle.

The next frequency-regulating circuit to be discussed is one similar to that used in certain Leland inverters. Before entering a discussion of that complete circuit, however, a portion of the circuit should be discussed. This portion in highly simplified form is shown in figure 6-30.

Two a-c voltages, E_1 and E_2, are half-wave rectified through diodes V1 and V2 and applied across a common capacitor. The voltages are 180° out of phase, so each tends to charge the capacitor in the direction indicated by its arrow. If E_1 is of greater magnitude, as shown, the capacitor is charged in the direction of the longer arrow, and with the polarity as marked. In the sine wave analysis, it can be seen that the peak charge (E_C) of the capacitor is the difference of peak E_1 and E_2, with those

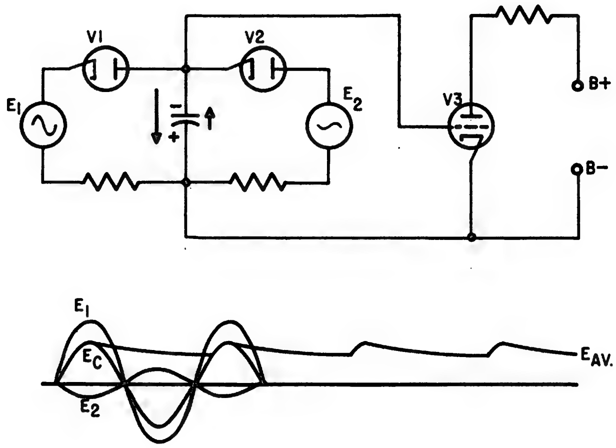


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Figure 6-30.—Simplified portion of Leland frequency regulator.

voltages exactly 180° out of phase. A variation in either voltage's magnitude or phase relation results in a change in the capacitor's charge. The capacitor is charged to a peak value of E_1 minus E_2 on the positive alternations, but has no low-impedance discharge path between alternations. Consequently, its voltage decreases very little between peak charges. Its resultant steady-state average wave thus appears as the d-c voltage E_{AV} on the sine graph in figure 6-30. Using E_{AV} as the control grid voltage on V3, the conduction of V3 is directly affected by any variations in the magnitude or phase relations of E_1 and E_2. For instance, if E_1 were decreased and E_2 were increased, their difference voltage E_{AV} would be reduced. The grid of V3 would become less negative, and V3's conduction would increase.

All of the operating principles just discussed apply to the more complete frequency regulator shown in figure 6-31.

The regulator's operation is as follows. Transformer T1 is supplied by the inverter's line a-c voltage, and its output is in turn applied through C1 and L1. Inductor L1's voltage (E_2) is impressed and half-wave rectified through diode V1A and C2. Line a-c voltage is also applied through R3, and a portion of it is tapped off and routed through R2 and C3. Capacitor C3's voltage (E_1), is impressed and half-wave rectified through diode V1B and C2. Voltages E_1 and E_2 tend to charge C2 in opposite directions.

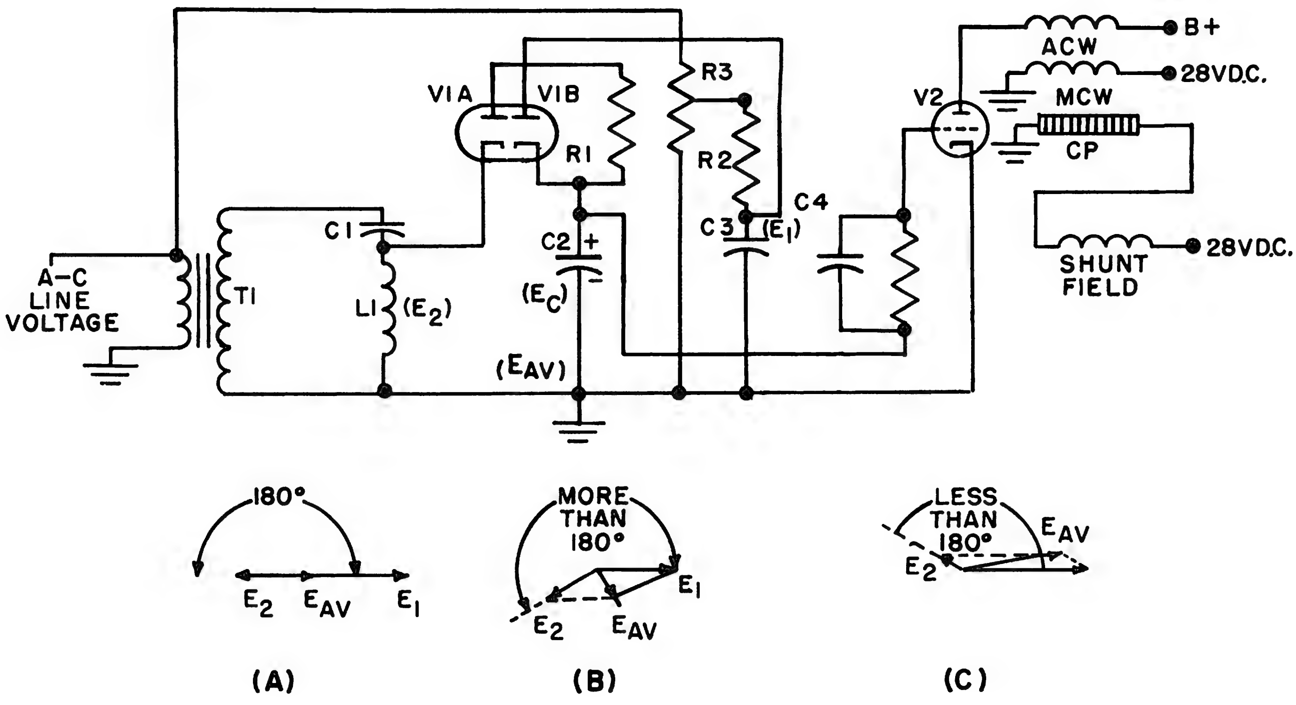

Figure 6-31.—Complete Leland inverter frequency regulator.

When the inverter is operating at the proper frequency (speed), the voltages E_1 and E_2 are 180° out of phase. Voltage E_1 is of greater magnitude, however, so E_{AV} across capacitor C2 has the polarity indicated. This condition is shown in vector diagram (A).

If inverter frequency rises, the inductive reactance of L1 increases and so does its voltage (E_2). Simultaneously, the capacitive reactance of C3 decreases, and so does its voltage (E_1). In addition, the two voltages move more than 180° apart, as shown in the vector diagram (B). Had inverter frequency decreased, rather than increased, the result would have been just the opposite in all respects, as shown in part (C). Note that E_{AV} of the magnitude shown in (A) is decreased in (B), but increased in (C). Since E_{AV} is applied to the grid of V2, any change of inverter frequency results in a change of V2 conduction. Any change in V2's conduction varies the current through the auxiliary carbon-pile control coil (ACW). Coil ACW is wound in magnetic opposition to the fixed main control coil (MCW). Therefore, any variation in ACW current (V2 conduction) affects the two coils' differential magnetic force acting on the carbon pile CP. Variations of carbon-pile compression cause variations of shunt field strength and result in corrective inverter speed changes.

SOLID-STATE VOLTAGE/ FREQUENCY CONTROL

A new solid-state voltage and frequency regulator that replaaes previous carbon pile and electronic tube regulators has been developed for certain Leland inverters. The unit, which uses semiconductor devices, requires much less maintenance time than older types.

The new regulator assembly (fig. 6-32) is comprised of four module subassemblies, each of which can be replaced separately, and their associated mounting hardware. These four subassemblies are a power supply module (A1), a topdeck panel module (A2), a frequency sensing module (A3), and a voltage sensing module (A4). A functional block diagram of this regulator is shown in figure 6-33.

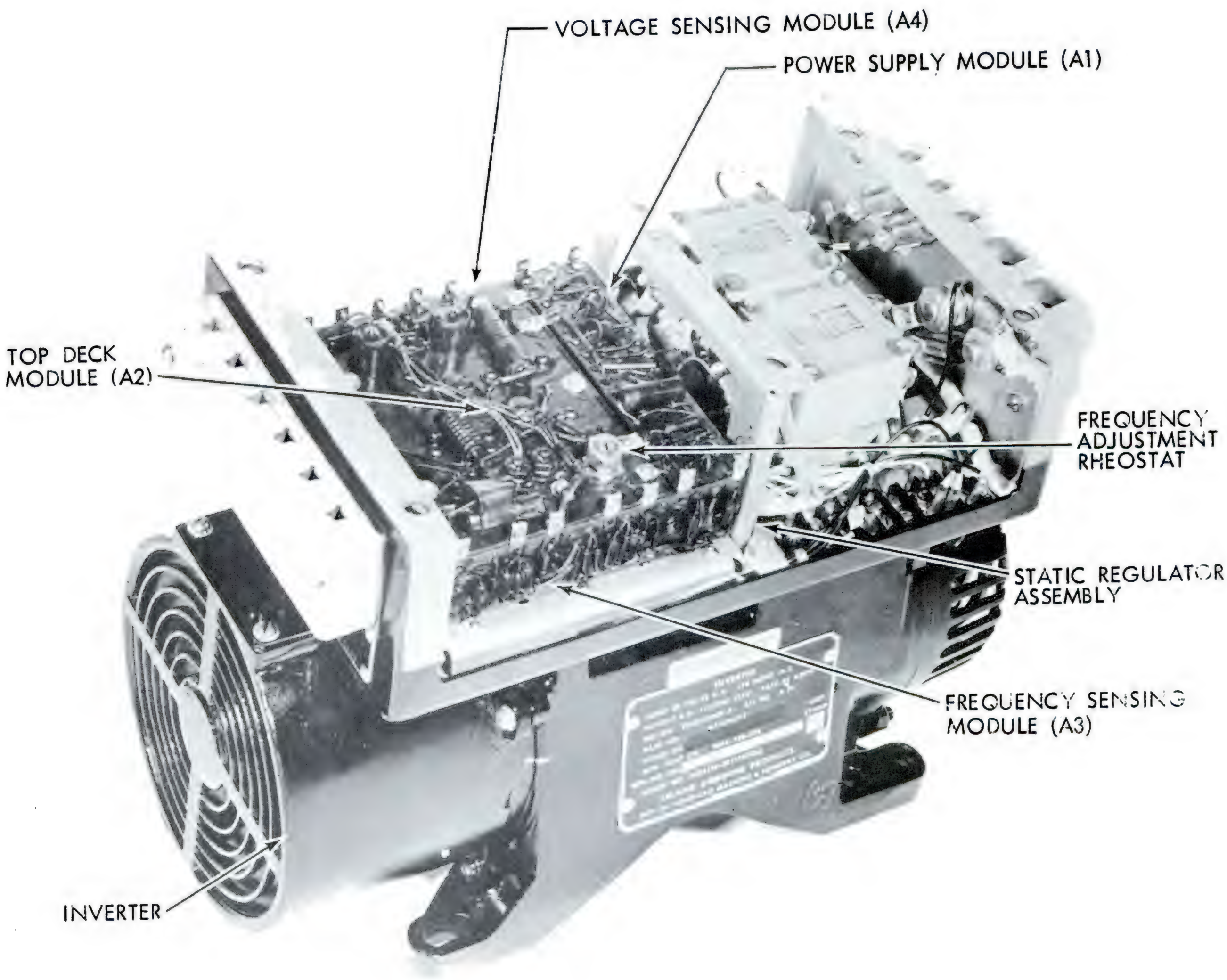

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Figure 6-32.—Inverter and regulator assembly.

Regulator Circuitry

Basically, the new regulator is a "pulse width" type of control which pulses 28 volt d-c power through the shunt field of the motor for speed control and through the exciter generator for output voltage control. The pulsed power through the shunt field of the motor and exciter generator is controlled by the switching action of two silicon-controlled rectifiers, SCR4 and SCR6 (A2 module). SCR4 is in series with the shuntfield of the motor, and SCR6 is in series with the exciter generator.

OPERATION OF THE SCR's.—Oscillator A4Q1 is a relaxation type oscillator, employing a unijunction transistor. This oscillator, synchronized to 800 hertz, "fires" SCR5 at an 800 hertz rate by applying a positive pulse to this SCR's gate terminal. Refer to figures 6-33 and 6-34. When SCR5 fires, capacitors A2C1 and A2C2 (fig. 6-34), are discharged through it. The capacitors then recharge rapidly through A2CR1,

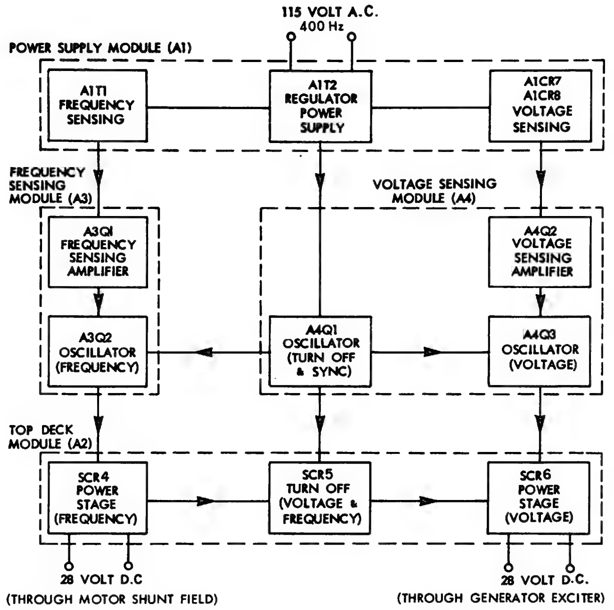

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Figure 6-33.—Functional block diagram of a regulator.

A2CR2, A2CR3, and A2CR7. This causes a sharp drop in the 28 volts d.c. on the anodes of SCR4 and SCR6, because the charging current for A2C1 and A2C2 that flows through A2CR1 and A2CR7 must flow through the shunt field of the motor, L5 (fig. 6-35), and the rest of the charging current that flows through A2CR2 and A2CR3 must flow through the exciter generator. Figure 6-36 shows this serrated 28 volts as E2. This is the anode waveform for SCR4 and SCR6. These SCR's can fire only when the anodes are positive and when the voltage E3 (fig. 6-36), is applied to their gate terminals from oscillators A4Q3 and A3Q2.

Without A4L1 inserted into the base B2 ground return, oscillator A4Q1 would produce a sawtooth waveform across A4C3. To understand its operation, assume that when a positive d-c voltage is applied to the top of A4R1 and base B1 from A1CR5 and A1CR6, the PN junction between the anode and base B1 becomes reversed biased. A few leakage electrons flow from A4C3 in the PN junction, slowly charging A4C3 to a positive potential. This continues until the PN junction becomes forward biased and a heavy conduction current commences to flow in the opposite direction, discharging A4C3. Now, during the small discharge time, a large electron flow exists between base B2 and the anode, and through A4L1. A4L1, being a saturable inductor, develops a spike of voltage during this time period. A4R2 is for damping the tendency of A4L1 to oscillate. The oscillator is synchronized at 800 hertz by the ripple, on the supply voltage from A1CR5 and A1CR6. Besides firing SCR5, the oscillator supplies sync signals to oscillators A3Q2 and A4Q3.

VOLTAGE REGULATION.—Oscillator A4Q3 is also controlled to some degree by changes in the inverter output voltage. The control is effected through A4Q2, an NPN transistor, which acts as a variable resistance in parallel with capacitor A4C5.

The voltage changes are delivered to the base of A4Q2 by rectifying the a-c output voltage of the inverter with A1CR7 and A1CR8. This negative d-c voltage is applied through A2R8 to terminal 7 of the terminal strip. A voltage adjustment level potentiometer R2 (fig. 6-35) is connected from terminal 7 to terminal 8, with the wiper arm and one end of the pot going to terminal 8. Therefore, any change in a-c output voltage is felt at the base of A4Q2 and causes oscillator A4Q3 to produce an output voltage spike that is either early or late with respect to the time of the positive voltage on the anode of SCR6. Refer to figure 6-36. Assume that the a-c output voltage from the inverter decreases. A base signal to A4Q2 and reduced conduction would result. The reduced conduction would cause A4C5 to charge to a higher voltage in a given time and oscillator A4Q3 to apply an output voltage spike to the anode of SCR6 at an early part of its anode voltage cycle. SCR6 would then allow current to flow through the exciter generator, G1 (fig. 6-35) for a longer period of time. This current is represented by E1 (fig. 6-36, the basic circuit is shown on the same figure. A greater exciter generator current would cause the a-c output of the inverter to rise to its normal level. An increase in a-c output voltage would cause opposite effects, reducing the conduction time of SCR6 during a cycle and lowering both the exciter generator current and a-c output voltage.

FREQUENCY REGULATION.—SCR4 functions in a manner similar to SCR6 to control the frequency of the inverter output voltage. The major difference is in the frequency-sensing circuitry. A1T1 is a transformer that is resonant above 500 hertz. Its secondary is connected to rectifiers A1CR1 and A1CR2 to provide the right side of the A2R2 with a negative d-c voltage

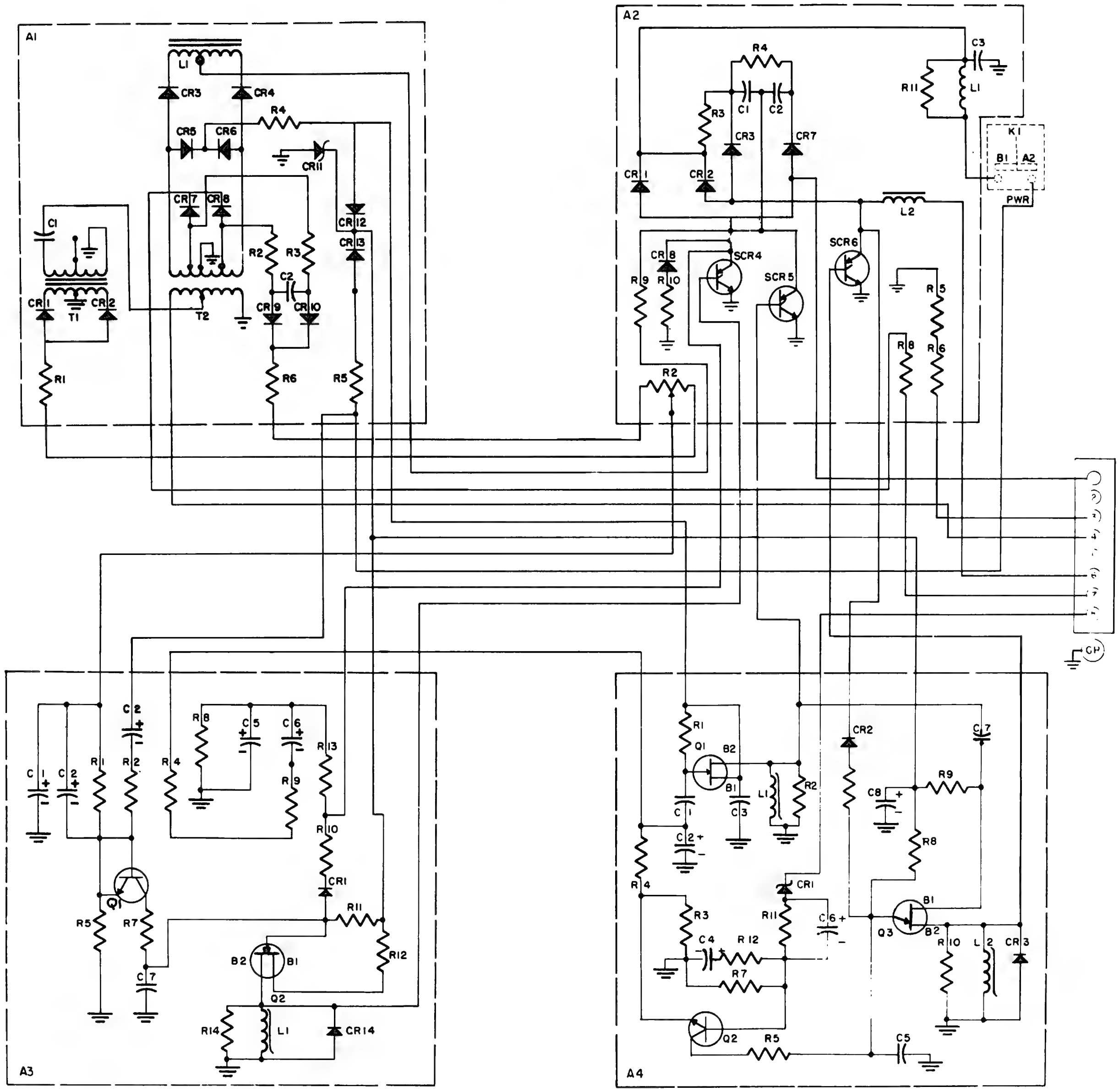

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Figure 6-34.—Regulator schematic diagram.

which varies directly as the frequency of the output voltage from the inverter: decreasing frequency causes a decrease in d-c voltage to A2R2. An unvarying positive d-c voltage is applied to the other side of A2R2 from rectifiers A2CR9 and A1CR10.

The wiper arm of A2R2 is connected to the base of A3Q1, an NPN transistor that acts as a variable resistance in parallel with capacitor A3C7 to control oscillator A3Q2. Each time the oscillator cycles, a pulse is fed to the gate of SCR4. The action and waveform are as shown in figure 6-36, except that the shunt field of the motor is the affected winding.

If a decrease in motor speed occurs, the following events take place. The rectifiers A1CR1 and A1CR2 produce a less negative d-c output voltage. This causes a greater drive to

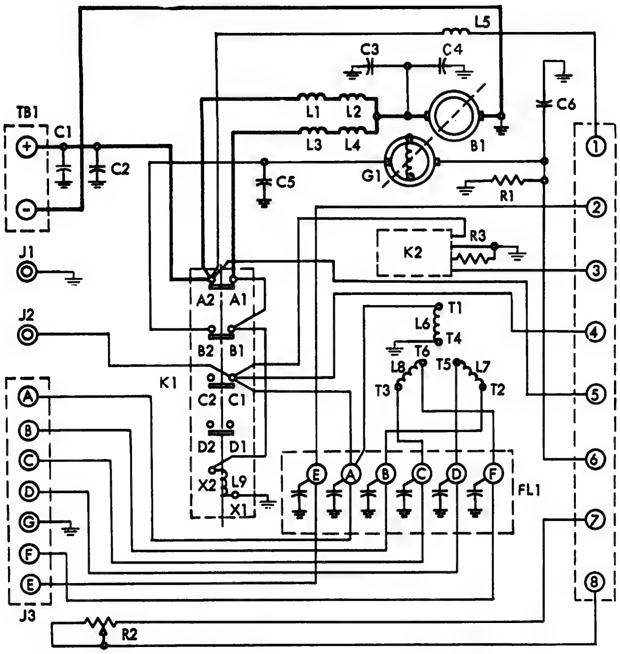

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Figure 6-35.—Inverter diagram.

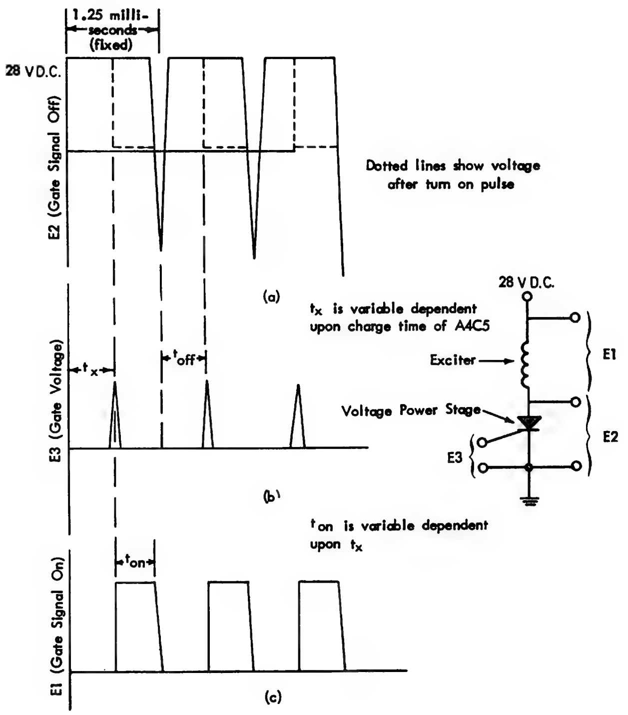

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Figure 6-36.—Anode waveforms.

the base of A3Q1 and a lower resistance in parallel with capacitor A3C7. Since this makes A3C7 charge more slowly, oscillator A3Q2 supplies a gate pulse to SCR4 at a later time in its anode voltage cycle. This results in less average current through the shunt field of the motor, increasing the speed of the motor and raising the frequency of the a-c output voltage.

TRANSISTOR POWER INVERTER

Push-pull transistor oscillators are very efficient devices for inverting d-c voltages to square-wave a-c voltages. Their reliability, compactness and efficiency make them suitable for a wide variety of applications. Thus, many equipments are using them as d-c plate supplies, replacing vibrator power units and dynamotors and the navy is presently developing units to replace aircraft rotating inverters.

Various a-c or d-c loads may be powered from the inverter. By selecting the proper rectifiers and filters, various d-c load voltage levels can be produced. If the rectifier is half-wave, the circuit need not be symmetrical; one transistor may be of a much lower power rating than the other. Operation of a-c loads may require that the output be filtered to produce a sinewave voltage. Where a-c loads require a precise input power frequency, the inverter frequency can be synchronized to a self-contained precision oscillator or use a limiter to control frequency.

ORIGINAL CIRCUIT

The original circuit (fig. 6-37), may be considered a self-excited, overdriven, transformer-coupled oscillator. It has also been described as a push-pull, free-running blocking oscillator. Basically, it replaces a nonsynchronous vibrator, but has no moving contacts. The low d-c voltage drop across a conducting power transistor is the basic property that allows the transistor to function as an efficient switch.

The necessary conditions for sustaining oscillations are: (1) the loop gain within the circuit must be greater than unity, and (2) there must be some means for switching the conduction from one transistor to the other to create both portions of the square wave. The first requirement is easily met by supplying positive

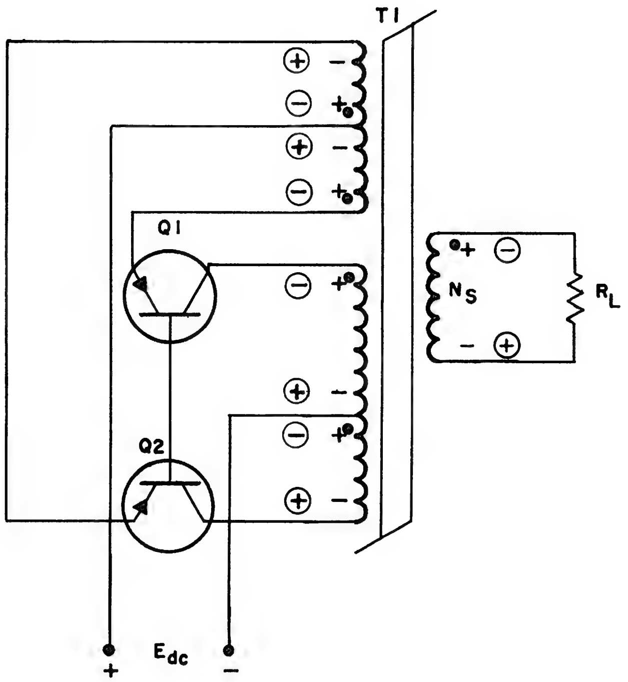

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Figure 6-37.—Basic circuit.

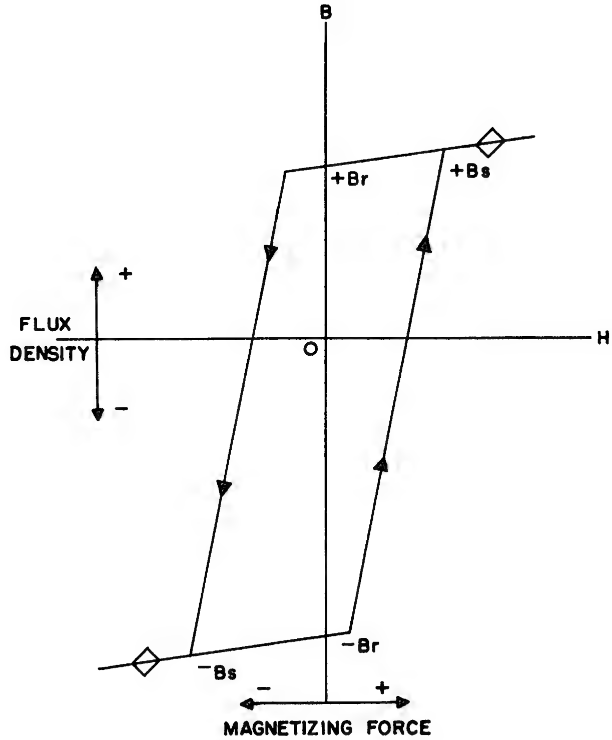

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Figure 6-38.—Rectangular B-H loop.

feedback to the emitters by use of a winding on T1. The second requirement is met by having the core material of T1 reach flux density saturation twice each cycle. Upon saturation, this effectively reduces the positive feedback sufficiently to cause the loop gain of the circuit to fall below unity, and the collapsing magnetic field causes one transistor to stop conducting and the other to begin.

The core material of the inverter transformer T1 is normally a material possessing a rectangular B-H loop, such as shown in figure 6-38. The core is usually a toroidal tape-wound core. Such a core is preferred because its characteristics provide abrupt flux density saturation and tight coupling of the windings. Abrupt saturation and steep sides on the loop allow the transistor to switch almost instantaneously from cutoff to heavy conduction; this minimizes the possibility of transistor failure.

The transformer windings of T1 (fig. 6-37) are marked with dots to show relative winding polarities. Transformer schematic drawings are never intended to show relative polarity unless marked with dots. This is so because the schematic drawing is neither intended to show the direction of the windings are placed on the core, nor whether they are all on the same portion of the core and cut in the same direction by the flux.

Operation of Original Circuit

Assume that the transistors are capable of conduction without emitter-to-base bias when the input voltage, E_{dc}, is applied. (Refer to figs. 6-37 and 6-38.) Some sort of circuit imbalance will cause one of the transistors to conduct more than the other. Assume that Q1 conducts more than Q2 at first, and that the flux density of the transformer core is initially set at -Br, possibly due to some previous operation. This conduction by Q1 causes a current to flow through the upper half of the collector winding. This current creates a positive magnetizing force for the core and induces a voltage in the collector-to-base winding of Q1 that is almost equal to E_{dc}. Induced voltages of all windings are as shown by the polarity markings which are not encircled in figure 6-37. Note that the induced voltages are in such a

direction with respect to the PNP transistor connections, as to drive Q1 into heavier conduction and cut off the conduction of Q2; with respect to the bases, a positive feedback voltage is applied to the emitter of Q1 and a negative voltage to the emitter of Q2. Also note that a voltage is induced into the lower collector winding which drives the collector Q2 negative with respect to the base, creating the requirement that the collector-to-base voltage rating of the transistors must be at least equal to $2E_{dc}$.

The induced voltage in the emitter-to-base winding of Q1 rapidly drives Q1 into heavy conduction, and the flux level of the core rapidly moves from -Br to +Bs. Once the flux level reaches +Bs, the core becomes saturated and produces a greater load on Q1, increasing its collector current at the moment before it stops conduction; the core magnetizing force is increased, but the flux level is not. Saturation also means that the positive feedback voltage for the emitter-to-base circuit of Q1 is interrupted. Core saturation, followed by heavy loading of the conducting transistor, is the mechanism for reducing the loop gain within the circuit to a value below unity in order that conduction may switch from Q1 to Q2, and vice versa. As saturation occurs, the conduction of Q1 induces no further voltages in any of the windings. However, the magnetic energy stored in the windings collapses and induces winding voltages that are of a reverse polarity from those previously induced. Although these latter induced voltages are low in amplitude, since the flux level change is small on the almost horizontal portion of the B-H loop to the right of +Br, they are effective in turning off Q1 and turning on Q2.

When Q1 reaches cutoff condition, the flux level will be at +Br. Q2 begins conduction, and the induced winding voltages that were previously created by the collapsing field are built up in amplitude. The polarity markings are shown encircled in figure 6-37. The negative magnetizing force which is now applied to the core drives the flux level from +Br to -Bs. Saturation occurs; positive feedback to Q2 is reduced; and the conduction switches back to Q1 and Q2 is cut off. The cycle of events becomes repetitive; and a square wave of voltage is applied across the load.

IMPROVED CIRCUIT

Several variations of the original common base circuit of figure 6-37 are possible. Associated with each circuit is some disadvantage or advantage which depends on the application. For instance, the common base circuit has the capability of compensating for the small voltage drop across the conducting transistor by the emitter-to-base feedback winding voltage. This is an advantage if the input is a very low value of E_{dc}. Its disadvantage, compared to other variations, is that an emitter current which is as large as the collector current flows in the feedback windings N_{fb}, requiring large wire for those windings.

Transistor circuits are discussed in detail in Basic Electronics, NavPers 10087-C.

Because of the stringent requirements for the transformer in the circuits previously discussed, an improved circuit (fig. 6-39), was developed. The saturating transformer T2, employed in this circuit is located in a different portion of the circuit from those described above. It is much smaller and does not need a toroidal core for good performance. The power transformer T1 does not saturate, and need not employ a toroidal core. Elimination of saturation from T1 removes the spike generation properties since there will be no heavy spike of collector current as before. Saturation now occurs in T2 to institute transistor switching, but its current is limited to a low value by a large resistance, R_{fb}. These transistors operate under less severe current and back voltage conditions than those discussed above. Also, the two transformers are less expensive than the single one in older circuits because they can use either "C" or laminated cores, each of which costs less and use cheaper bobbin type windings.

Several variations of this circuit, having particular features adapted to the specific needs of the application made of it, are possible.

NEW DEVELOPMENTS IN AIRCRAFT INVERTERS

Considerable effort is being put forth to develop a high-powered inverter that can replace rotating inverters in aircraft. Figure 6-40 is the circuit diagram of such a unit, and is presented to indicate a future application.

This unit is intended to be a 250-volt-ampere, 3-phase or single-phase, 400-Hz inverter. There are three oscillators of the improved circuit type shown in figure 6-39. One is a master oscillator. The other two are synchronized in frequency and phase to the master

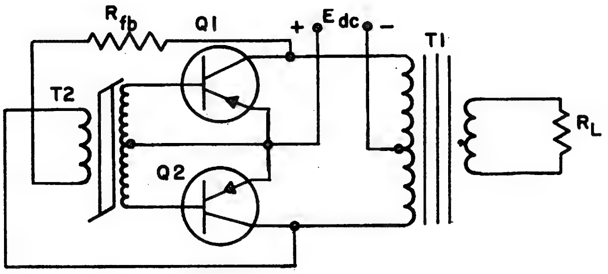

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Figure 6-39.—Improved circuit.

oscillator. There are also phase angle sensing and control circuitry.

The slave oscillators (fig. 6-40) are synchronized by injecting a small voltage into the base circuits from the master oscillator. This voltage is from the NT windings. Phase angle sensing and control is accomplished by two discriminators and control stages. Terminals T1, T2, T3, and T0 would be connected to the output of the oscillators. The two diode discriminators compare the line-to-neutral voltage of phases 1 and 2 to a voltage derived from between the neutral of a 3-phase transformer connected between the line terminals and the inverter neutral. When the two neutrals do not coincide, an a-c voltage is found to exist between them that indicates the magnitude and direction of error. The discriminators compare this error voltage with the line-to-neutral voltages of phases 1 and 2. The outputs of the discriminators, which may be zero, positive or negative, is applied to the two controlling transistors.

The two controlling transistor stages serve as variable a-c resistances in the collector-to-base feedback circuits of the two slaved oscillators, whose a-c resistance is controlled by the output of the discriminators, and by the amplitude of the feedback voltage. The bridge rectifiers, around each controlling transistor, serve as limiters to control frequency and supply d-c voltages for the transistors. Thus, these networks control phase, frequency, and amplitude by controlling the feedback voltages to the transistor bases. Control of phase or frequency is possible in this manner because the oscillator frequency is directly proportional to the rate-of-change of the flux of the transformer, or to the induced voltage in the feedback transformer. The master oscillator also employs a limiter for frequency control.

A-C SYSTEM PROTECTION

With the incorporation of high-capacity a-c power systems in naval aircraft, there came the accompanying problems of protecting both the aircraft and its a-c system from a number of possible fault conditions. Such foreseeable conditions included power feeder cables shorting to ground (ground fault), improper system voltage (voltage fault), and improper system frequency (frequency fault). A discussion of each type of fault follows.

GROUND-FAULT PROTECTION

Preventive Ground-Fault Protection

This type protection is basically in the realm of installation and design practices, aimed at preventing a ground fault from occurring in the first place. A few examples of preventive action are: adequate insulation and isolation of buses, insulated junction boxes, and extra insulation in critical areas. However, protection of a corrective nature must also be provided, because ground faults may occur despite all preventive measures.

Corrective Ground-Fault Protection

This type protection comes into use after a ground fault has occurred, mainly to prevent fire or damage to the aircraft. The primary function of protective networks or devices is usually to disable a faulty power system. However, some devices designed to provide this protection also have a secondary feature; that of isolating only the damaged or faulty portion of a system, when possible, and thus permitting continued use of the undamaged portions. These may be referred to as dual-function devices.

Single-function devices do not permit continued use of the undamaged portions, but function only to disable and isolate an entire power system when a fault occurs anywhere in the system's protected portions. These portions include only the generator, its power feeder cables, and the bus to which it is connected. (Branch circuits coming off the bus have their own fuses and circuit breakers.)

The type of device to use in a particular a-c power system is dictated by the nature of the

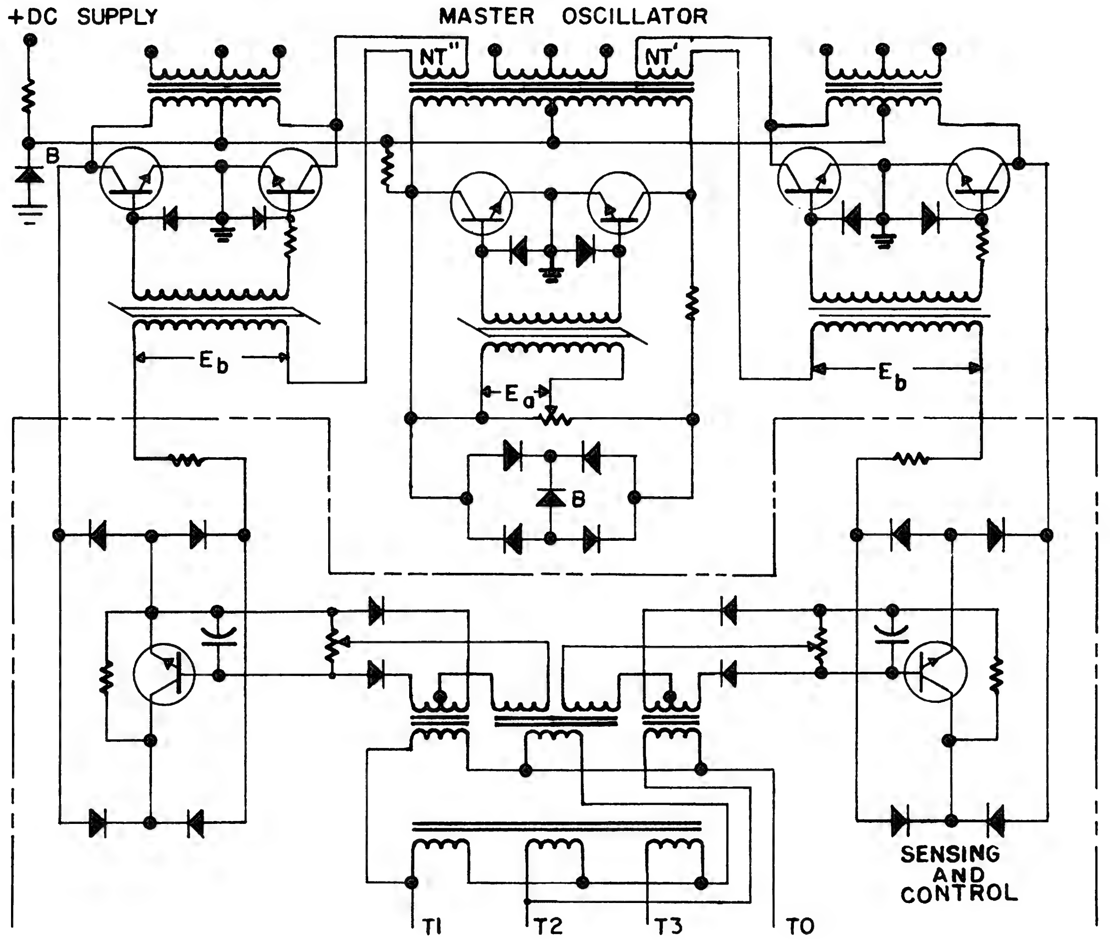

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Figure 6-40.—Transistorized aircraft inverter schematic.

equipment supplied by that particular system. All such equipment must fall into at least one of the following categories:

1. Vital equipment required at all times to maintain controlled flight.
2. Equipment needed to perform the aircraft's mission, but not necessary for controlled flight.
3. Convenience equipment not necessary for either of the above mentioned items.

Obviously single-function devices could not be used in systems supplying power for category (1) equipment. On the other hand, it would not be necessary to employ dual-function devices in systems supplying power for category (3) equipment. The choice of device for category (2) would depend on the importance of the aircraft's mission. An additional feature of both dual- and single-function devices and networks is their fail-safe design. This feature is incorporated wherever possible. If a protective device, circuit, or network is fail-safe, this means that the protected a-c power system is not disabled should the protective equipment itself fail.

Figure 6-41 illustrates two typical general methods currently employed to provide ground-fault protection. Both are designed fail-safe. Part (A) is a differential-relay single-function method, and part (B) is a fuse mesh dual-function method. In part (A), the two current transformer outputs are connected in opposition across the differential relay coil. If either the hot feeder cable or the ground feeder cable becomes grounded, then the currents through

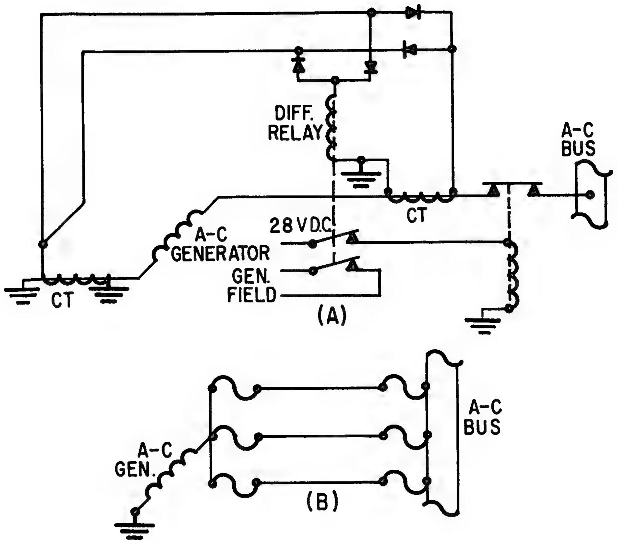

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Figure 6-41.—(A) Single-function protector; (B) dual-function protector.

the two cables are unequal, and this results in unequal current transformer output voltages. The differential of these voltages operates the differential relay, which opens the generator field, and disconnects the generator's feeder cable from the bus. This method is fail-safe to the extent that if one or both of the interconnecting leads become either open or grounded, this protective circuit failure does not cause the generator to be disabled.

Part (B) of figure 6-41 is the dual-function method. If a ground fault occurs on any one of the three feeders, the fuses at the ends of the faulted feeder will open. This isolates only the faulted portion, while permitting continued use of the rest of the system.

OVERVOLTAGE-FAULT PROTECTION

Under normal conditions, system a-c voltage is controlled by the voltage regulator. However, to cope with forseeable voltage-fault conditions not controllable by the regulator, provisions for backup voltage-fault protection are needed in a-c power systems. These provisions are made in a number of different ways, for different aircraft, and the best way to familiarize yourself with any certain method or device is to consult the Overhaul Instruction Manual, or the Maintenance Instructions Manual.

One means of obtaining overvoltage protection is by the use of fuses in the power feeders. These are the same fuses which also serve as ground-fault protectors. The ampere rating of these fuses is such that nontransient overvoltages cause sufficient overcurrent to open the fuses, before serious damage occurs.

Where an overvoltage tripping relay protective mode is used, its general circuitry is usually similar to that shown in figure 6-42. The average of all three phase voltages is translated through T1 and the rectifiers into an average d-c voltage which is applied to the coil of the trip relay. When a high-voltage fault occurs, the trip relay interrupts the d.c. to the a-c power contactor, opening it, and disconnecting the a-c generator from its bus. Trip-voltage adjustment is made with R1.

UNDERFREQUENCY FAULT PROTECTION

During certain phases of a-c generator operation, it is necessary to prevent the generator's output from being connected to its normal loads. One of the most common of these is during a low-frequency output condition, such as

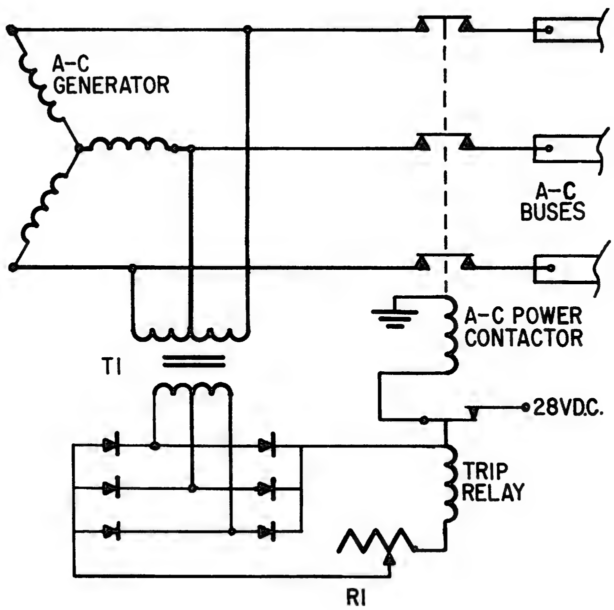

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Figure 6-42.—Overvoltage protector circuit.

when the generator has been started but has not reached full speed. Another is when the generator has been shut down and slows below a safe output frequency. The generator may be connected or disconnected, as needed, through the use of any of a number of frequency-sensitive devices.

The simplest of these employs a speed switch which closes when the a-c generator's prime mover attains a safe speed (frequency). This speed switch simply opens or closes the circuit to the main a-c power contactor. In general, a mechanical speed-switch controlled circuit is not as sensitive as an electrically controlled circuit and so is used where the allowable frequency range is relatively wide.

Where frequency protection must be limited to a narrower range of generator speed, the electrical type is generally used. The operating principles of the most common electrical types are similar to those of the circuit shown in figure 6-43.

Line voltage is applied through C1 and R1, so that a certain portion of voltage appears across each when line frequency is correct. The voltage of R1 is applied through C2 to a parallel circuit consisting of C3 and L1 in one leg, and C4, R2, CR1, and the trip relay coil in the other leg. This parallel circuit is resonant at 400 hertz. Due to the characteristics of resonant parallel circuits, the impedance, and consequently the voltage drop, is maximum across points A and B (E_{AB}) when line frequency

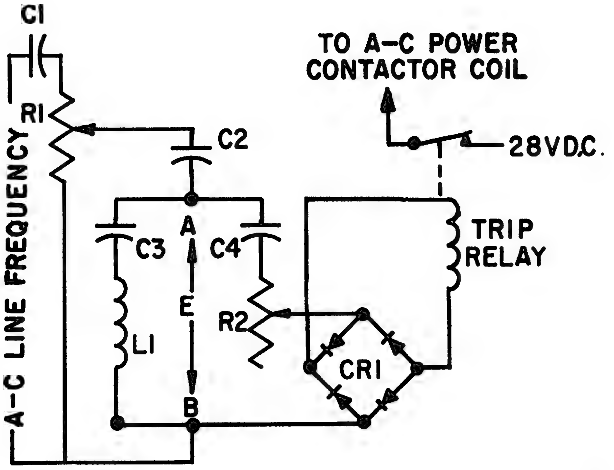

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Figure 6-43.—Electrical underfrequency protector.

is 400 hertz. A portion of this voltage appears across the trip relay coil and holds its contacts closed. When line frequency decreases; however, more voltage is dropped across C1, so less voltage is impressed across the parallel circuit. In addition, the parallel circuit goes off resonance with the change in frequency, its impendance drops, and a greater percentage of R1's output voltage is dropped across C2. Thus two effects have combined to reduce the voltage through C4, R2, CR1, and the trip relay coil. A still greater reduction in R2-CR1-trip relay voltage takes place because the decreasing frequency causes a greater percentage of E_{AB} to be dropped across C4. When the decrease of line frequency is great enough, the resultant decrease in trip relay coil voltage causes the relay's contacts to open. This in turn opens the main a-c power contactor, and the a-c generator is disconnected from the bus. Coarse adjustment of the trip frequency is made with R1, and fine adjustment is made with R2.

PHASE SEQUENCE PROTECTION

When a load is to be shared by two a-c generators, or where a given load may be supplied by more than one generator at different times, provisions must be made for indicating relative generator phase rotation prior to connecting an a-c generator to the bus. A common situation where such protection is needed is where an external a-c power unit may be connected to an a-c system normally supplied by the aircraft a-c generator. If the aircraft a-c generator is connected to the load with a positive phase rotation, it would not be allowable to use an external power unit with a negative phase rotation. A phase sequence-sensitive relay designed to prevent this is shown in figure 6-44.

The unit consist of three filter networks, one sensitive only to a positive phase sequence, and the other tow sensitive to a negative phase sequence. The output of two of the networks, marked POS. and NEG., operate their associated coils. When the a-c phase sequence at terminals A, B, and C is in the proper direction, the POS. coil is energized. If the phase sequence is reversed, the NEG. coil is energized. D-c voltage from the COM. terminal is connected either to the POS. SEQ. terminal, or NEG. SEQ. terminal, depending on which relay coil is energized. Thus, external power contactor K1 may be closed only when the external power

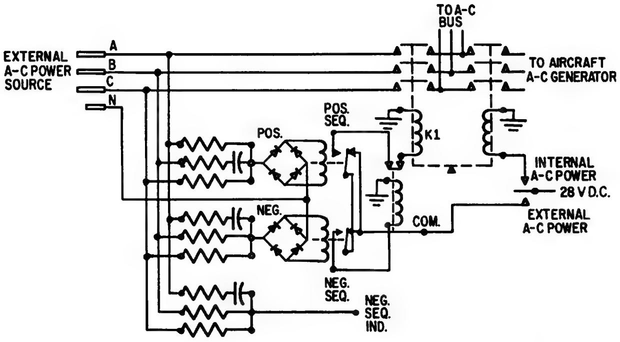

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Figure 6-44.—Phase sequence relay.

source has the correct phase rotation. The third filter network is sensitive only to a negative phase rotation, and provides a voltage for a light or other warning device.

POWER DISTRIBUTION BUS

The power distribution bus system differs somewhat with each aircraft. The type system utilized is determined by the type and amount of equipment installed and the overall mission of the aircraft. However, manufacturers of naval aircraft are required by contract specifications to provide a normal distribution system and, in the event of a complete power loss, an emergency power and distribution system.

NORMAL DISTRIBUTION

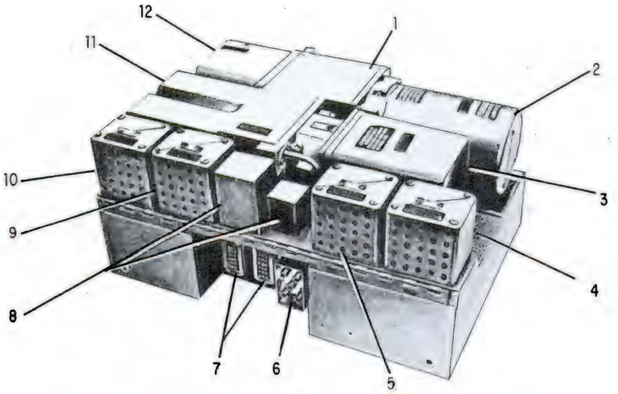
Under normal conditions, power is received from the generator or generators through the line contactor and is distributed to the various buses. In the case of a two generator system, the right generator supplies power to the essential bus while the left generator supplies power through the bus transfer contactor to the monitored bus. The purpose of the transfer relay is to insure that power is directed to the essential bus if one generator should fail. The monitored bus would at this time also be disconnected from the supply.

EMERGENCY

In the event of a complete a-c or d-c electrical system failure, emergency power is supplied to the essential buses by the emergency power system. One of the many different methods of supplying this emergency power is by employing a ram air turbine generator which may be extended into the airstream upon indications of a power supply failure. Once the generator is extended, emergency power is available for the essential buses only. Transfer from the normal system to the emergency system is completely automatic after the emergency generator has been extended. However, should the normal system recover, the emergency system is automatically disconnected from the essential buses by the emergency power transfer relays.

CHAPTER 7
AIR DATA COMPUTER SYSTEMS

Modern supersonic aircraft, such as the F-4B, have complex automatic flight control and weapons systems whose operation depends upon precise information concerning the air surrounding the aircraft. The air data computer (ADC) receives information from pressure-sensitive and temperature-sensitive units mounted on external points of the aircraft; it compensates the inherent errors and relays the corrected information to other systems in the aircraft. Concurrently, it detects any changes in the pressure and temperature information and converts these into usable signals which are relayed along with the pressure and temperature signals. The electrical signal outputs are representative of altitude, Mach number, true airspeed, angle of attack, total temperature, and impact pressure. There is also a pneumatic output of corrected static pressure, which is used by the cockpit instruments (barometric altimeter, airspeed, and vertical speed indicators) and by some modules within the air data computer.



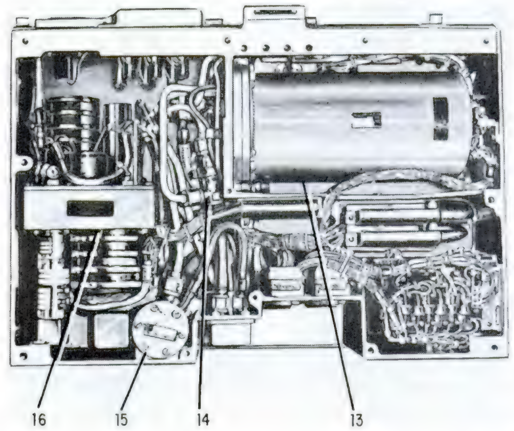


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Figure 7-1.--Air data computer. (A) Top rear view; (B) bottom view.

COMPONENT DESCRIPTION

ELECTROMECHANICAL ANALOG COMPUTER

The air data computer is an electromechanical analog computer, which is composed of a base assembly (chassis) and the computing sections. The chassis contains all the interconnecting harnesses, and it provides the housing for the modular computing sections. Utilization of plug-in modules assures easier maintenance of the system. Figure 7-1 (A) is the top, rear view of the ADC; figure 7-1 (B) is the bottom view.

Nomenclature for figure 7-1.

1. Gearbox module.
2. Pressure ratio transducer module.
3. Log pressure controller module.
4. Total temperature amplifier module.
5. True airspeed amplifier module.
6. Pneumatic connector.
7. Electrical connectors.
8. Power transformers.
9. Static pressure compensator amplifier module.
10. Log pressure controller amplifier module.
11. Gearbox potentiometer cover.
12. Mach sector assembly module.
13. Static pressure compensator module.
14. Jet ejector.
15. Pressure regulator.
16. Total temperature and true airspeed servo module.

POWER SOURCES

The power required for operating the ADC is both electrical and pneumatic. The required electrical power is 115 volts a.c., 400-Hz, 3-phase, and 28 volts d.c. Other voltages are applied to output potentiometers within the ADC by the systems that require ADC data. The pneumatic power required is from 14 to 250 psig, which is supplied by the engine.

PRINCIPLES OF OPERATION

There are four data inputs supplied to the ADC—total pressure, indicated static pressure, indicated angle of attack, and total temperature. There are other command and test signal inputs that only use the available raw or corrected primary data for making functional tests of various systems which use ADC outputs. The complete input and output signal groups can be seen in figure 7-2.

DATA INPUTS

Before proceeding with the principles of operation of the ADC, it is essential to understand the nature of the primary data inputs. They are defined in the following paragraphs.

Indicated Static Pressure

Indicated static pressure is the atmospheric pressure as sensed at a point on the aircraft which is relatively free from airflow disturbances. At subsonic speeds, static pressure error is small and of little significance; but at transonic and supersonic speeds, extreme static pressure errors are sensed at the static ports. The error magnitude is regarded as the ratio of true static pressure to indicated static pressure, as related to Mach number and angle of attack.

Total Pressure

Total pressure is the sum of static air pressure and the pressure created by the motion of

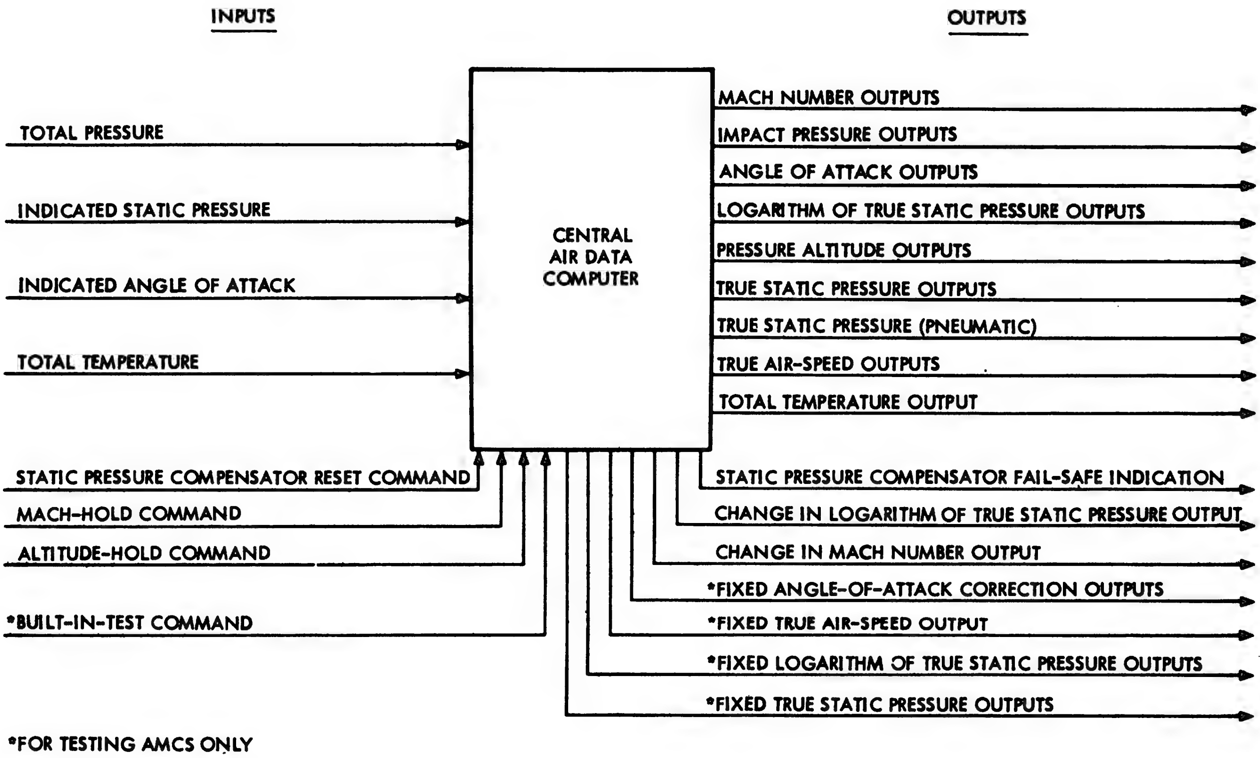

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Figure 7-2.—ADC signal input and output data.

the aircraft through the air. Total pressure is sensed by the pitot tube, which is the same as the more familiar term—pitot pressure. Total pressure is relatively free from error and is therefore uncorrected.

Total Temperature

Total temperature is the temperature of ambient air plus the temperature increase created by the motion of the aircraft. Total temperature is sensed by a platinum resistance element inside an aerodynamic housing placed in the airstream. The resistive element, whose resistance varies with temperature, acts as the variable portion of a bridge circuit.

Indicated Angle of Attack

The aircraft angle of attack is the angle of the aircraft in relation to the direction of motion of the aircraft. The angle-of-attack probe senses the angular direction of air relative to longitudinal datum line of the aircraft. The angle-of-attack input to the ADC is in the form of voltage per degree of indicated angle of attack.

SYMBOLS USED WITH AIR DATA COMPUTER

Table 7-1 is a list of symbols referred to in this chapter and their respective definitions. These symbols should be memorized so that they can be correlated with the ADC flow diagram shown in figure 7-3. As shown in the flow diagram, indicated static pressure (Psi) is connected to the static pressure compensator (SPC). Through controlled means, Psi is used as a reference so that true static pressure (Ps) may be generated and supplied to the logarithm pressure controller (LPC) and the pressure ratio transducer (PRT). In the LPC the pneumatic input (Ps) is converted to two mechanical outputs, representative of Ps and the natural log of Ps, which is symbolically LnPs. In the PRT the pneumatic inputs of Ps and Pt (total pressure) are compared, producing a resultant mechanical output of Ps/Pt. Each of these functions will be explained in detail in this chapter.

Table 7-1.—Symbols used with ADC.

Symbol	Definition
TAS	True airspeed
Tt	Total temperature
αi	Indicated angle of attack
αt	True angle of attack
Mn	Mach number
ΔMn	Incremental change in Mach number
Pt	Total pressure
Qc	Impact pressure
LnQc	Natural logarithm of impact pressure
Ps	Corrected static pressure
Psi	Indicated static pressure
LnPs	Natural logarithm of static pressure
ΔLnPs	Incremental change in natural logarithm of corrected static pressure
SPS	Static pressure sensor
SPC	Static pressure compensator
LPC	Log pressure controller
PRS	Pressure ratio sensor
PRT	Pressure ratio transducer
Hp	Pressure altitude
Pv	Vacuum pressure (lower than ambient pressure)
Pg	Gage pressure (higher than ambient pressure)
Pr	Engine bleed air pressure
Pe	Exhaust pressure
θr	Ramp angle
f	Function (used in computation)
F	Function (ADC output)
Po	Pressure in evacuated bellows
AMCS	Airborne missile control system

STATIC PRESSURE COMPENSATOR

As mentioned previously, both Mach number and angle of attack will cause significant errors in the static pressure system. Indicated static pressure (Psi) as detected by the aircraft static ports, will deviate from true static pressure; these deviations have a definite relationship to Mach number and angle of attack, which is shown by the graph in figure 7-4.

The graph (fig. 7-4) shows the amount of error is indicated static pressure for five different angles of attack, which range in aircraft speeds from Mach 0.2 to Mach 2.0. Although the error curve for each angle of attack is definitely different from each of the others, a radical deviation occurs similarly for all of them during transonic speeds of the aircraft. From approximately Mach 0.94 to Mach 1.06, the Ps error increases more rapidly than at any other speed. The static pressure compensator must correct these errors so that true static pressure is available to the remainder of the system and the

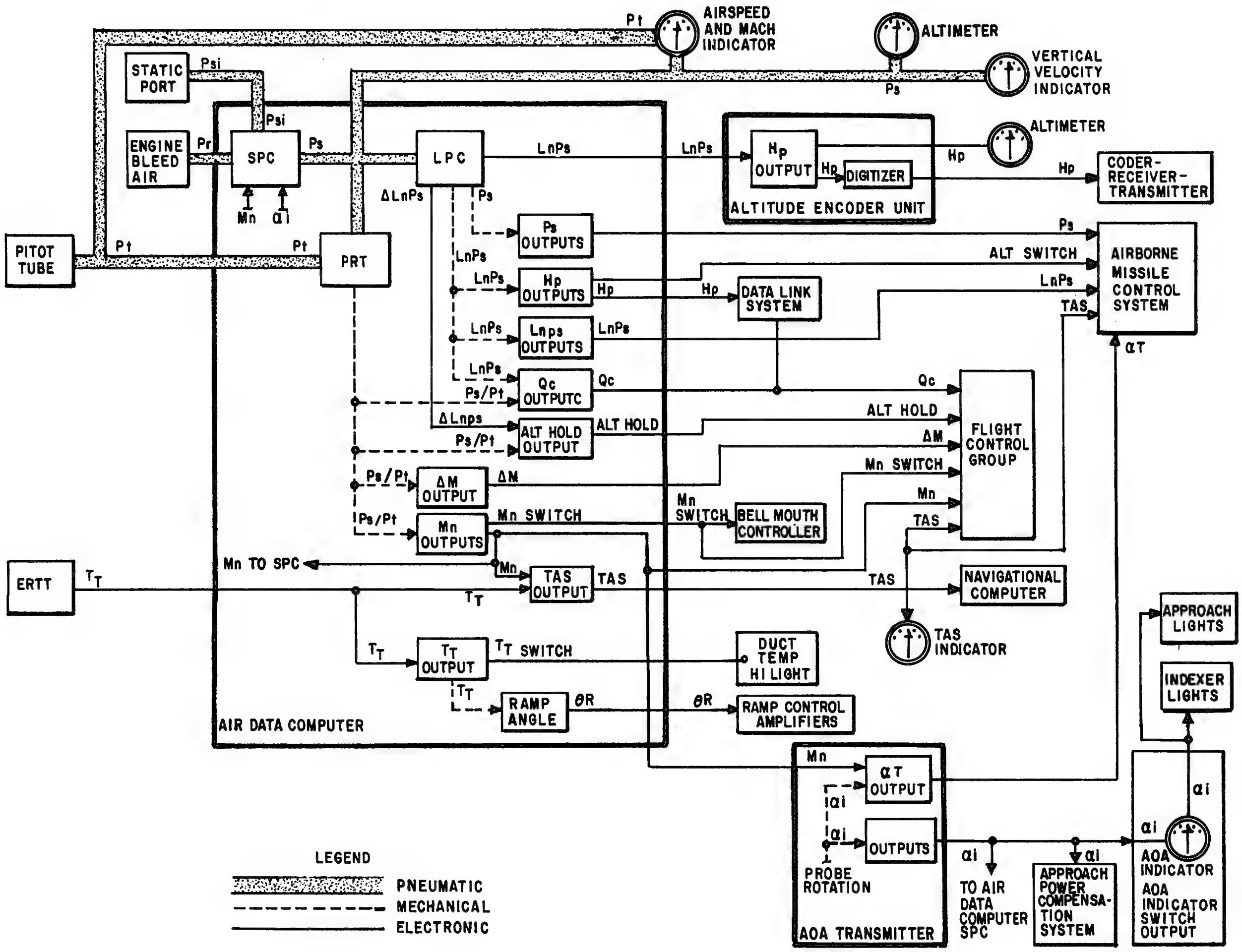

Figure 7-3.—ADC data flow diagram.

aircraft. Figure 7-5 is a schematic diagram of the static pressure compensator.

Figure 7-5 shows how the SPC produces true static pressure. Essentially, this is done by regulating the case pressure within the SPC so that it becomes true static pressure. Indicated static pressure is compared with case pressure, compensations for aircraft speed and angle of attack are introduced, and any needed pressure corrections are sensed. If case pressure is too low, a pressure line is opened until true static pressure is reached. If case pressure is too high, a vacuum line is opened until the proper amount of pressure is released. Fail-safe circuitry provides for direct transfer of Psi to the Ps load lines in case of SPC failure. Should a malfunction cause pressure to build up inside the SPC case, a pressure-relief valve open to prevent damage to the SPC.

The heart of the SPC is the force balance instrument, or balanced beam. It receives the command (or compensation) signals in the form of a change of fulcrum and actuates the control valves for pressure or vacuum as needed.

In more detail, Psi from the static pressure ports of the aircraft is applied to the SPC via the input line shown in the upper right portion of figure 7-5. The input line is connected to the fail-safe solenoid valve and to the Psi diaphragm. At the diaphragm, case pressure (Ps) opposes Psi, resulting in the difference force of Psi - Ps being applied to the beam at point B.

At point A, an evacuated bellows, whose expansion is determined by Ps, applies a downward

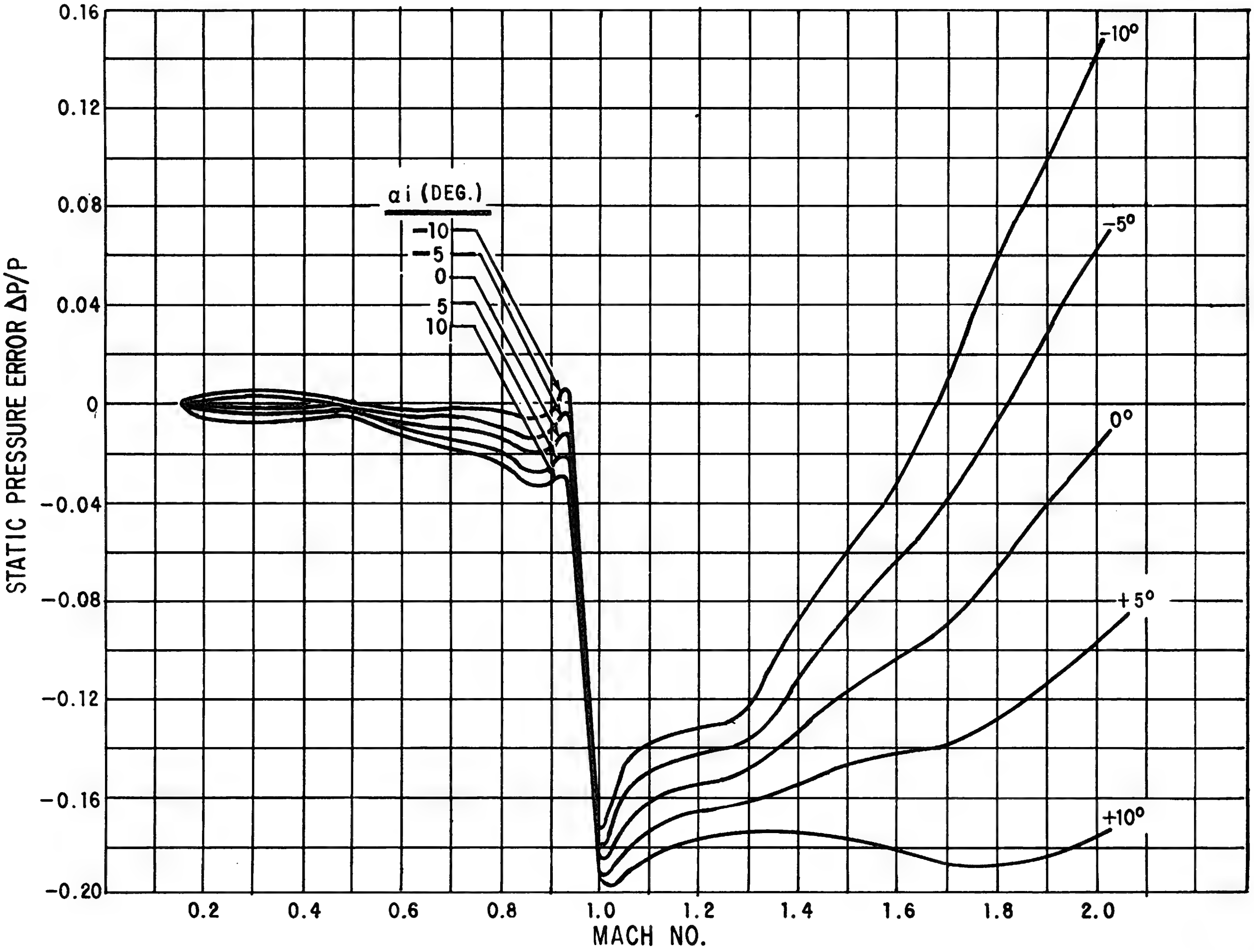

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Figure 7-4.—Static pressure compensator curves.

force on the beam relative to Ps. When the force (Psi - Ps and Ps) multiplied by their respective distances from the fulcrum are equal, the beam is balanced. This signifies that case pressure is accurately regulated and is true static pressure.

Should the fulcrum position be changed, the beam will tip in response to the unbalance. For example, if the B end of the beam tips downward, it indicates more pressure if needed inside the SPC. The physical arrangement is such that, when the beam moves downward, the flexure attached to the beam also moves downward, opening the control valve to the Pg (higher pressure) line. This allows pressurized air to enter the case until the beam again becomes balanced, closing the Pg control valve. Had the B end of the beam moved upward, the cause would have been excessive pressure inside the case. Therefore, the flexure would have moved upward, opening the valve to the Pv (vacuum) line, letting out the excess pressure until the beam rebalanced.

As was mentioned earlier, indicated static pressure will deviate from true static pressure while the aircraft is in flight. At transonic and supersonic speeds, the deviations will be greater and will vary with aircraft attitude. Because of this, SPC corrections must be made a function of both Mach number (Mn) and indicated angle of attack (αi). The circuitry shown in the lower half of figure 7-5 illustrates how this is accomplished.

For explanatory purposes, resistors R15, R33, and R37 can be disregarded. They are

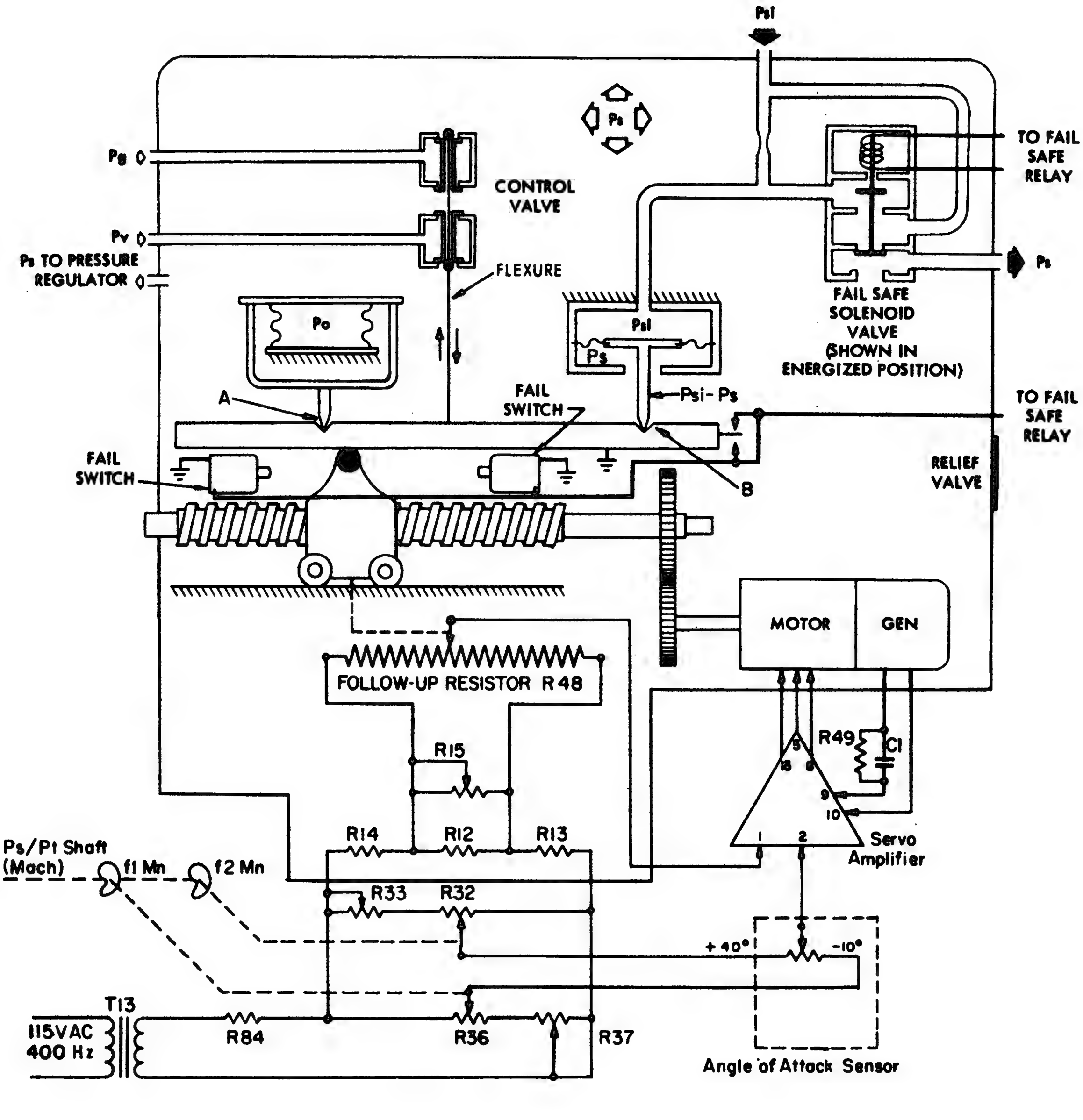


Figure 7-5.—Schematic diagram of static pressure compensator.

calibration resistors and their presence is of no concern at this time. The wipers of potentiometers R32 and R36 are positioned by two Mach function cams f1 (Mn) and f2 (Mn). Their electrical outputs are coupled to opposite sides of the C potentiometer in the angle-of-attack transmitter. Thus, the voltage applied to the potentiometer equals f1 minus f2, or the voltage difference between the wipers of R32 and R36.

Since the f1 and f2 function cams are revolved by rotation of the Ps/Pt (Mach) shaft, positioning of the two potentiometer wipers is related to Mach number. Therefore, at zero Mach the two wiper voltages are equal, indicating no airspeed and no voltage drop across the angle-of-attack potentiometer. As airspeed is increased, a voltage differential between the wipers causes current flow through the angle-of-attack potentiometer and the attitude of the

aircraft determines upon which portion of the potentiometer its wiper rests. It should be noted at this time that all three angle-of-attack potentiometer wipers are driven by rotation of the angle-of-attack probe, but only the C potentiometer is used here.

The indicated angle of attack deviates from true angle of attack while the aircraft is in flight for the same reasons that Psi deviates from Ps. Placement of the angle-of-attack probe on the aircraft and the effects of airstream buffeting cause erroneous indications. Because these are known effects, it is possible to compensate for them. Function cams f1 and f2 are machined in such a way as to correct the two deviations (intercept and slope), and maintain the correct ratio of output voltage per degree of angle of attack across the αi potentiometer which supplies the Mach correction voltage for the SPC.

The correction (or command) signal is applied to the servoamplifier, where it is amplified to an amount sufficient to drive the servomotor. The mechanical output from the motor operates a tachometer-generator (for servoamplifier feedback) and rotates the gears driving the jackscrew. As the jackscrew turns, the fulcrum carriage is moved toward the desired position. It can be seen in figure 7-5 that the carriage is mechanically linked to the slider on the followup resistor R48. R48 serves as a feedback resistor whose output is fed to the servoamplifier to cancel the effects of the command signal when the fulcrum is at the correct position. Better correlation of this can be obtained by referring to figure 7-6, which is the servoamplifier schematic diagram.

Case pressure is supplied to the Ps load lines through the normally energized fail-safe solenoid valve. If the SPC fails, the solenoid valve is deenergized and Psi is connected into the Ps load. Should this occur, a warning light in the cockpit indicates the failure. Included in the fail-safe circuitry is a time-delay relay and a holding relay. The static pressure compensator fail-safe circuitry can be seen in figure 7-7. After 0.3 second, the time-delay relay drops out if the beam becomes unbalanced or if the 115-volt a-c supply to the fulcrum-positioning servo is interrupted. The holding relay (which controls the solenoid valve) deenergizes if the 28-volt d-c power is interrupted or if the time-delay relay trips.

The manually operated RESET switch, located in the cockpit, permits control of the solenoid valve. If the malfunction causing the relay to trip has cleared, the solenoid valve can be energized again by this reset switch. However, if the malfunction still exists, the reset switch will have no effect.

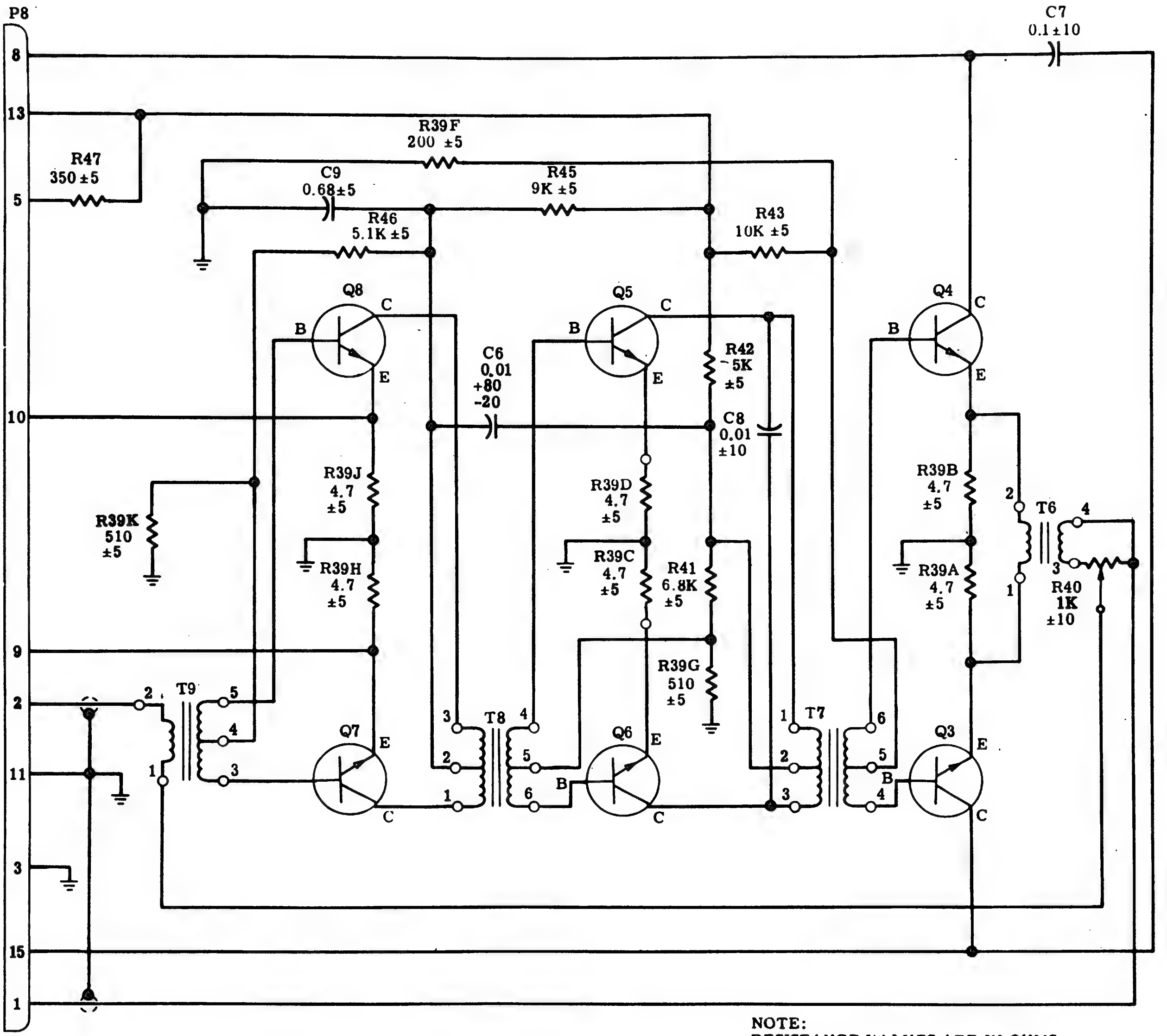
To supply air pressure that is above ambient for use by the SPC, engine bleed air (Pr) is coupled to the pressure regulator. There, Pr becomes Pg, and is compared with the SPC case pressure by means of a bellows-diaphragm arrangement and regulated to maintain a correct Pg to Ps ratio. It is then connected to the Pg control valve. A Pg output from the pressure regulator is also fed to the jet pump to develop vacuum pressure (Pv). Pv is developed by the venturi effect in the jet pump and is connected to the Pv valve in the SPC.

PRESSURE RATIO TRANSDUCER

The correct angular displacement of the Ps/Pt shaft is one of the basic operations of the computer, for it provides the Mach number and Mach hold output reference. The Mach output from the pressure ratio transducer is derived from the inputs of Ps (corrected static pressure) and Pt (total pressure), since the difference between the two pressures is directly attributed to aircraft speed.

As in the SPC, a force balance instrument is used in the pressure ratio transducer to establish the mechanical reference point for compared pressures. However, the PRT utilizes the balanced beam in a manner slightly different from that used in the SPC. Since the PRT produces a mechanical instead of a pneumatic output, a beam imbalance is detected electrically, the signal is amplified, and a servomotor drives a gear chain to produce both the Mach output and the beam correction. Figure 7-8 is the functional diagram of the PRT.

Pressure difference sensing occurs in the pressure ratio sensor (PRS), a plug-in unit mounted inside the PRT. Corrected static pressure and total pressure inputs are applied pneumatically to the PRS, with Ps entering the case and Pt applied to a differential pressure bellows. Corrected static pressure controls the expansion of an evacuated bellows, which exerts a force equal to static pressure on one end of the balanced beam. On the other end of the beam, the differential bellows applies a force equal to Pt - Ps. The point of beam-balance, therefore, represents the ratio of static pressure to total pressure or Ps/Pt.



NOTE:
RESISTANCE VALUES ARE IN OHMS
CAPACITANCE VALUES ARE IN MICROFARADS

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Figure 7-6.—Servoamplifier schematic diagram.

At the left side of the PRS (fig. 7-8) is an E-core transformer, which derives it name from the core shape. The center leg of the transformer, which is shorter than the two outside legs, holds the exciter winding, to which 400-Hz a.c. is applied. The pickup windings on the two outside legs are series-connected, but are wound in opposite directions. An iron armature on the end of the balanced beam is suspended between the two outer core legs, adjacent to the center leg. When the beam is balanced, the space between the movable iron core and each of the outer legs is equal. Because the two windings are wound in opposite directions and connected in series, voltages induced in the two windings are 180° out of phase and equal in amplitude. As a result, they cancel each other and produce no appreciable output signal.

If the beam is unbalanced by a change in either Ps or Pt (or both), the iron core will be moved closer to one of the two outer windings

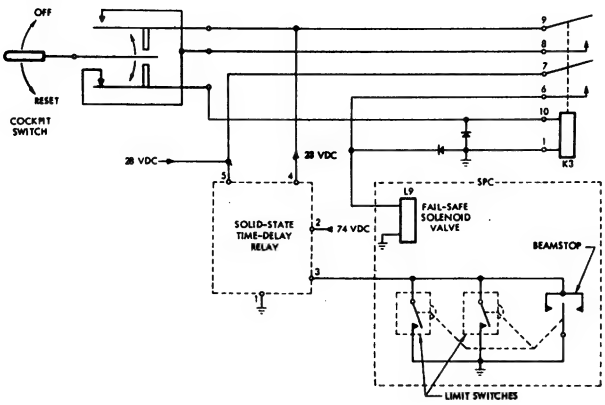

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Figure 7-7.—Static pressure compensator fail-safe circuit

and farther away from the other. The permeance of the magnetic path from the center leg through the movable core and back through the outer leg is directly affected by distance. Therefore, as the core moves closer to one of the outer legs, the induced signal increases in the nearer winding and decreases in the winding farther from the movable core.

Because the induced voltages in the two windings on the outer legs are 180° out of phase, the resultant output voltage is equal to the difference between the two, with the amplitude representative of the amount of beam displacement. The phase of the output is that of the larger voltage and indicates the direction of beam displacement.

External to the PRS, but within the PRT, are the servoamplifier, servomotor, and gears required to correct beam displacement and furnish the output of Ps/Pt (Mach). Their operation is very similar to that of the servo loop within the SPC. An error signal is applied to the input of the servoamplifier, where it is amplified to an amount sufficient to drive the servomotor. The direction of servomotor rotation is determined by the phase of the input error signal. While driving the gears in the proper direction to rebalance the beam and correct the Mach output, the motor also drives a tachometer-generator whose output is applied to the servoamplifier as an inverse feedback to stabilize the servo operation.

When the carriage is driven to the proper point to rebalance the beam, the signals induced in the two outer windings of the E-core transformer once again become equal and opposite, canceling each other. Since no error signal is applied to the servoamplifier, the motor stops and the Mach output (Ps/Pt) shaft is positioned at the correct angular displacement.

LOGARITHM PRESSURE CONTROLLER

To supply a usable altitude reference for the automatic flight and missile control systems, it is necessary to convert static pressure from its pneumatic form to a mechanical output representative of Ps. Because logarithmic quantities can be multiplied or divided by simple addition and subtraction and that the natural logarithm of static pressure varies in an almost linear manner with altitude in feet, a logarithm pressure controller (LPC) is used.

LPC Outputs

The outputs of the LPC are (1) a shaft rotation equivalent to the natural logarithm of static pressure (LnPs), (2) a shaft rotation equivalent to static pressure (Ps), and (3) a synchro output equivalent to incremental changes in the natural logarithm of static pressure (ΔLnPs).

LPC Operation

The operation of the LPC (fig. 7-9) is quite similar to that of the PRT. In each unit a plug-in pressure sensor is used, and each sensor operates on the balanced beam principle. The major difference between the two units is that only one pneumatic input is applied to the LPC, requiring a different method of applying torque to one end of the balanced beam.

Corrected static pressure from the SPC is supplied to the static pressure sensor (SPS) inside the LPC. The expansion of an evacuated bellows, which exerts pressure on one end of the balanced beam, is affected by the amount of Ps. As illustrated in figure 7-9, pressure is exerted on the other end of the beam by a torsion bar. If the two applied torques are equal, the beam is balanced and there is no output.

Should an imbalance occur, the beam moves in response to the strongest applied torque. This causes the movable core (on the end of the balanced beam) to move closer to one of the two E-core transformer pickup coils, and farther away from the other. The resultant output signal is coupled to the external servoamplifier, amplified, and connected back to the

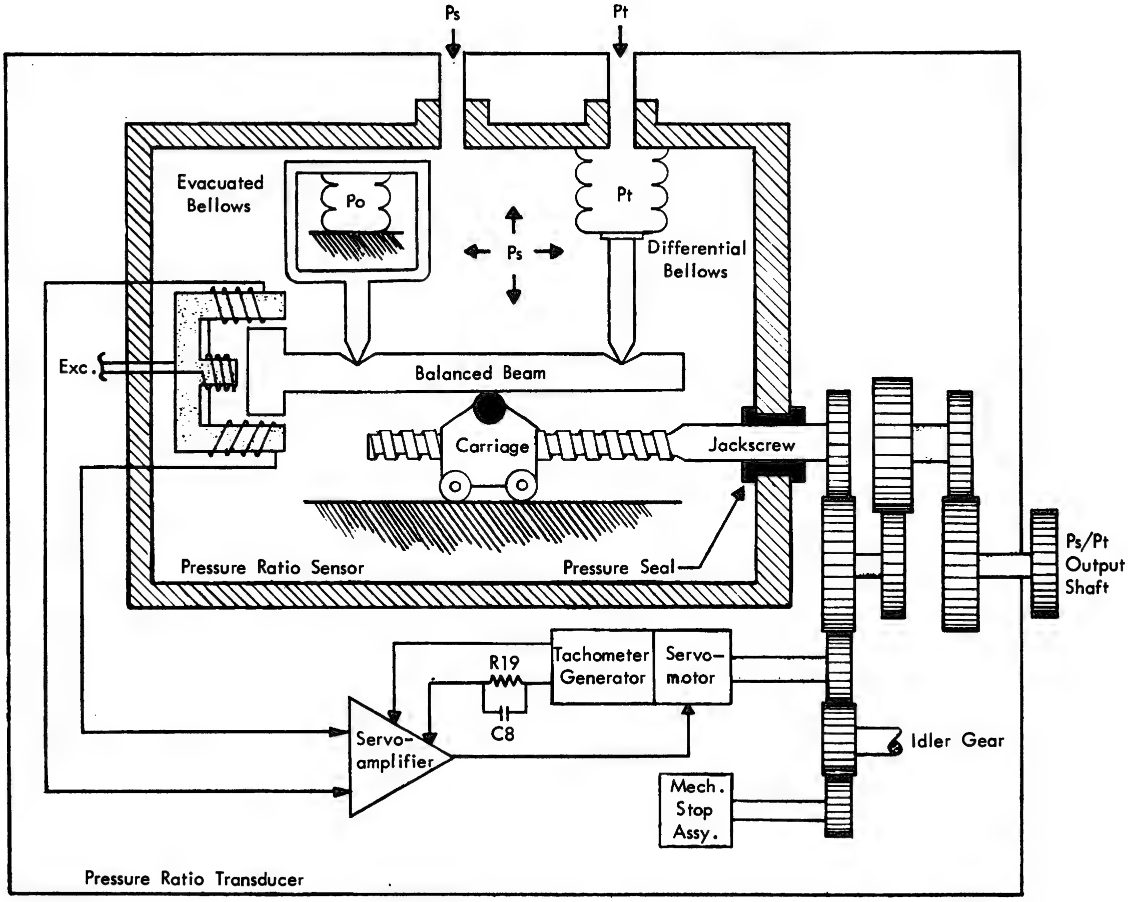

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Figure 7-8.—Functional diagram of the pressure ratio transducer.

servomotor which drives the gear train to rebalance the beam. As with the PRT, the LPC servomotor drives a tachometer-generator which supplies an inverse feedback to the servoamplifier for motor stabilization.

The SPS carriage assembly has a noticeably different structure from that of the PRS carriage. This structure difference consists of a torsion bar applying force at one end of the beam and a linearizing cam to vary the amount of torque applied by the torsion bar. It was mentioned earlier that the natural logarithm of static pressure varies in an ALMOST LINEAR manner with altitude in feet. The linearizing cam compensates for the slight nonlinearity so that a true logarithmic output is obtained.

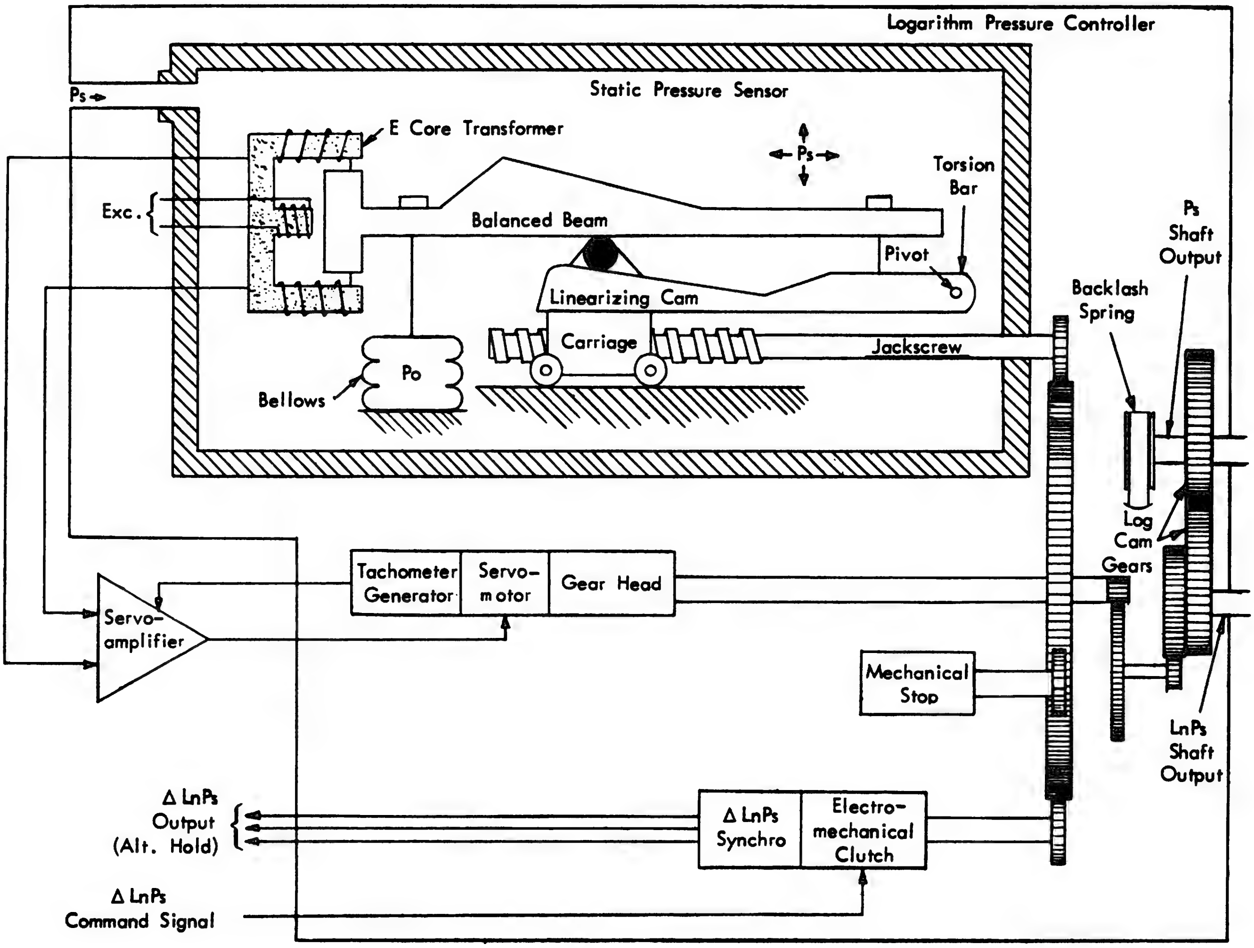

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Figure 7-9.—Functional diagram of logarithm pressure controller.

To obtain the Ps shaft output, a pair of cam gears, cut to produce the antilog of LnPs, translates rotation of the LnPs shaft into Ps rotation. A mechanical stop is included in the LPC to limit rotation of the LnPs shaft to a range of - 1,000 to +70,000 feet elevation.

In addition to the two mechanical outputs, an electrical output representative of ΔLnPs is taken from a synchro inside the LPC. An electromechanical clutch keeps the synchro disconnected from the LnPs output shaft until ALT HOLD mode is selected in the automatic flight control system (AFCS). When this occurs, the command signal energizes the clutch, which mechanically connects the synchro rotor to the output shaft. The rotor then rotates with altitude changes and provides an electrical output that is an analog of ΔLnPs. The phase of the output signal indicates the direction of altitude change. The synchro has an incremental range of plus or minus 200 feet of altitude at sea level.

Tt AND TAS SERVO ASSEMBLY MODULE

The total temperature and true airspeed servosystems are combined in a two-part module (fig. 7-10) which may be removed from the ADC as a single unit. One part of the module contains Tt components; the other contains TAS components.

Total temperature shaft mechanization is obtained as shown in figure 7-11. The Tt circuitry consists of a balanced bridge in which the

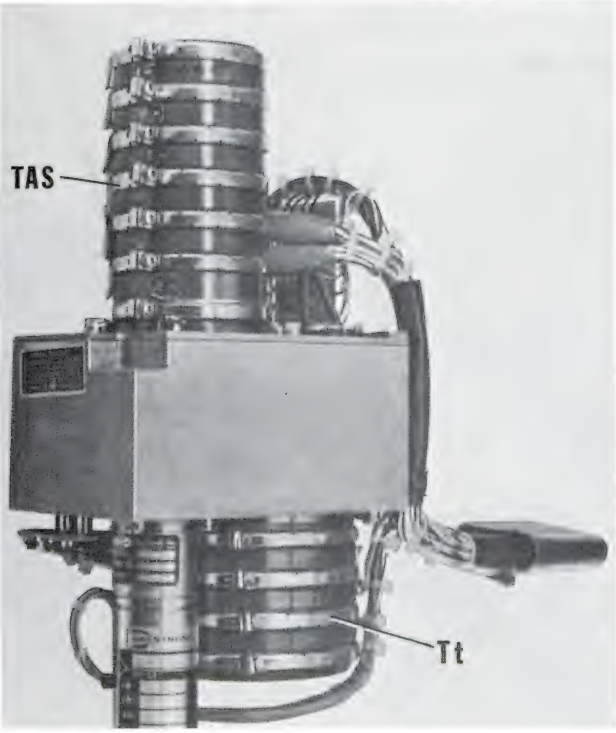

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Figure 7-10.—TAS and Tt servo module.

magnitude of current is a function of total temperature and a servosystem which converts the electrical signals to a mechanical output. The mechanical output is then converted into electrical signal inputs to the ramp control system. The ramps, which are variable intakes, control the velocity of the intake air being inducted into the engine when the aircraft is flying at supersonic speeds.

Excitation voltage is applied to the bridge circuit from transformer T13, which produces a current in each half of the bridge. When the bridge is balanced, the two servoamplifier inputs (one from each side of the bridge) will be of equal amplitude and there will be no error signal.

Error (or temperature change) signals are introduced into the bridge circuit by the total temperature sensor, which is contained in an aerodynamic probe mounted in the airstream. The temperature sensed by the total temperature sensor is the sum of the ambient temperature and the temperature that is produced by the deceleration of the air flowing into the probe. Since the speed of sound is dependent upon absolute temperature and that the sensor element resistance varies as a function of temperature, any temperature change results in a change of bridge balance and, therefore, a change of bridge current. The imbalance creates a difference voltage between the two servoamplifier inputs, whose amplitude is proportional to the amount of temperature variation and whose polarity indicates the direction of variation.

Since the computation of true airspeed requires total temperature information as well as Mach number, some of the circuit components used for Tt mechanization are also used in the TAS bridge. This may be seen in figure 7-12.

The theory of operation is similar to that for the Tt bridge circuit; however, the TAS bridge has two variable reference signals (Mn and Tt) instead of one. Bridge circuit excitation is supplied by transformer T13, which also supplies excitation for the Tt bridge.

As illustrated in figure 7-12, the TAS servoamplifier inputs are taken from the wipers of R29 and R60A. Positioning of the R29 wiper is determined by a Mach function cam, thereby making that servoamplifier input a function of both Mach number and total temperature. R60A is the followup potentiometer, whose output is electrically referenced to the angular position of the TAS output shaft.

The TAS output shaft is driven in the same manner as is the Tt output shaft, with the angular shaft position representative of true airspeed.

Additional potentiometers and switches whose outputs are controlled by the Tt and TAS shafts are labeled accordingly in both figure 7-11 and figure 7-12.

MACH SECTOR ASSEMBLY MODULE

The Mach sector assembly module contains a series of cam-operated potentiometers. The cams are mounted on the gear-driven Ps/Pt shaft as shown in the block diagram in figure 7-13. Table 7-2 lists the Mach potentiometer functions.

COMPUTER GEARBOX MODULE

The computer gearbox performs mechanical computations in response to shaft rotation inputs from the PRT and the LPC. The PRT input is a function of Mach (Ps/Pt shaft) and the LPC supplies Ps and LnPs references. The computer gearbox may be understood more easily if

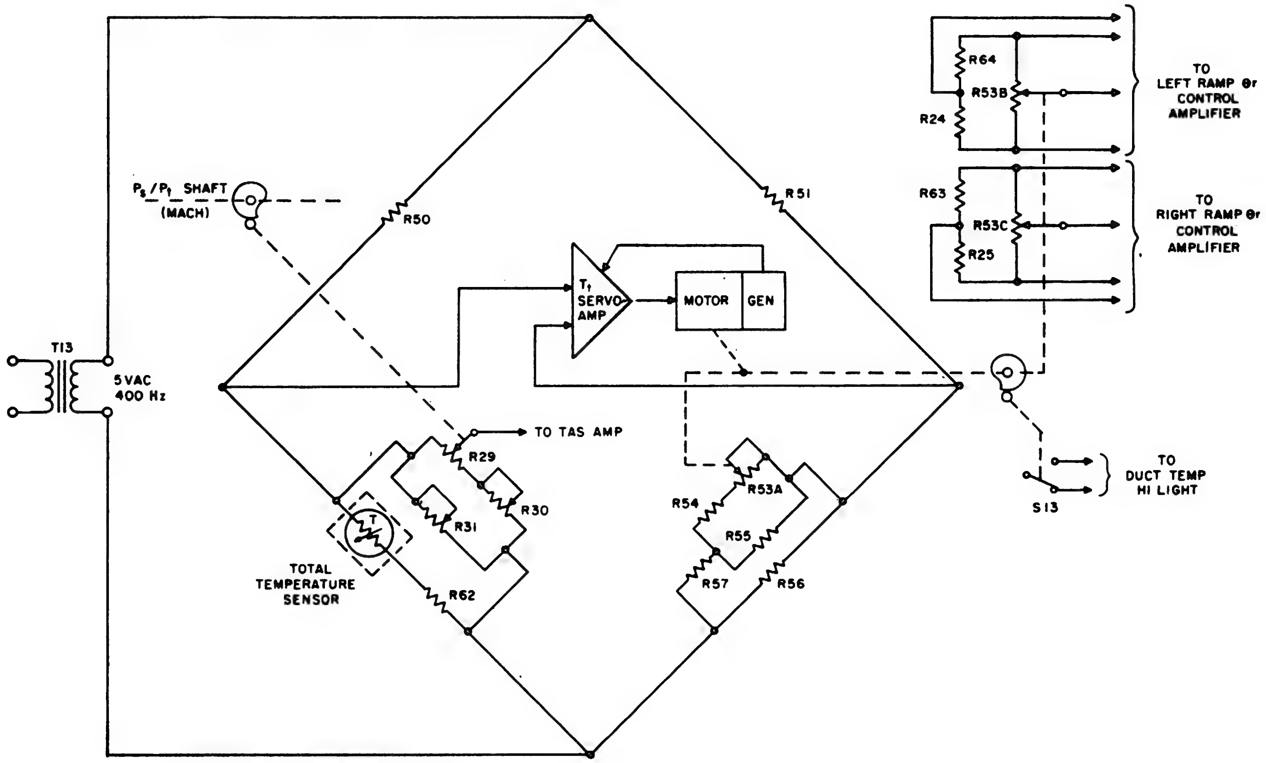

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Figure 7-11.—Functional diagram of Tt shaft mechanization.

discussed operation by operation. Therefore, refer to both figure 7-13 and figure 7-14.

Ps Potentiometer Assembly

The two potentiometers in the Ps potentiometer assembly (fig. 7-13) provide the AMCS with electrical signals proportional to static pressure. The tap outputs supply a voltage equal to a known static pressure for AMCS built-in-test (BIT) functions.

LnPs Potentiometer Assembly

The LnPs potentiometer assembly provides electrical outputs proportional to the natural logarithm of static pressure. Outputs from both R20A and R20C go to the AMCS and each has taps to furnish BIT altitude voltage to the AMCS. R20D and R20E are not used at the present time.

Altitude Switches

The altitude switches consist of three cam-operated switches that are also driven by the LnPs shaft. The cams are situated in the correct positions to actuate the switches at specific altitudes.

Potentiometer Assembly

The Qc potentiometers furnish electrical outputs representative of LnQc to the automatic flight control system. The wipers of the Qc potentiometers are driven by the LnQc shaft. LnQc shaft rotation is derived from two mechanical inputs—one from the LnPs shaft, and the other from the Ps/Pt shaft. The LnPs input from the LPC is coupled by a spur gear to one input of a mechanical differential. A cam on the Ps/Pt shaft generates Ln(Qc/Ps) which is inserted at the opposite side of the differential. The LnQc output shaft drives the three wipers of

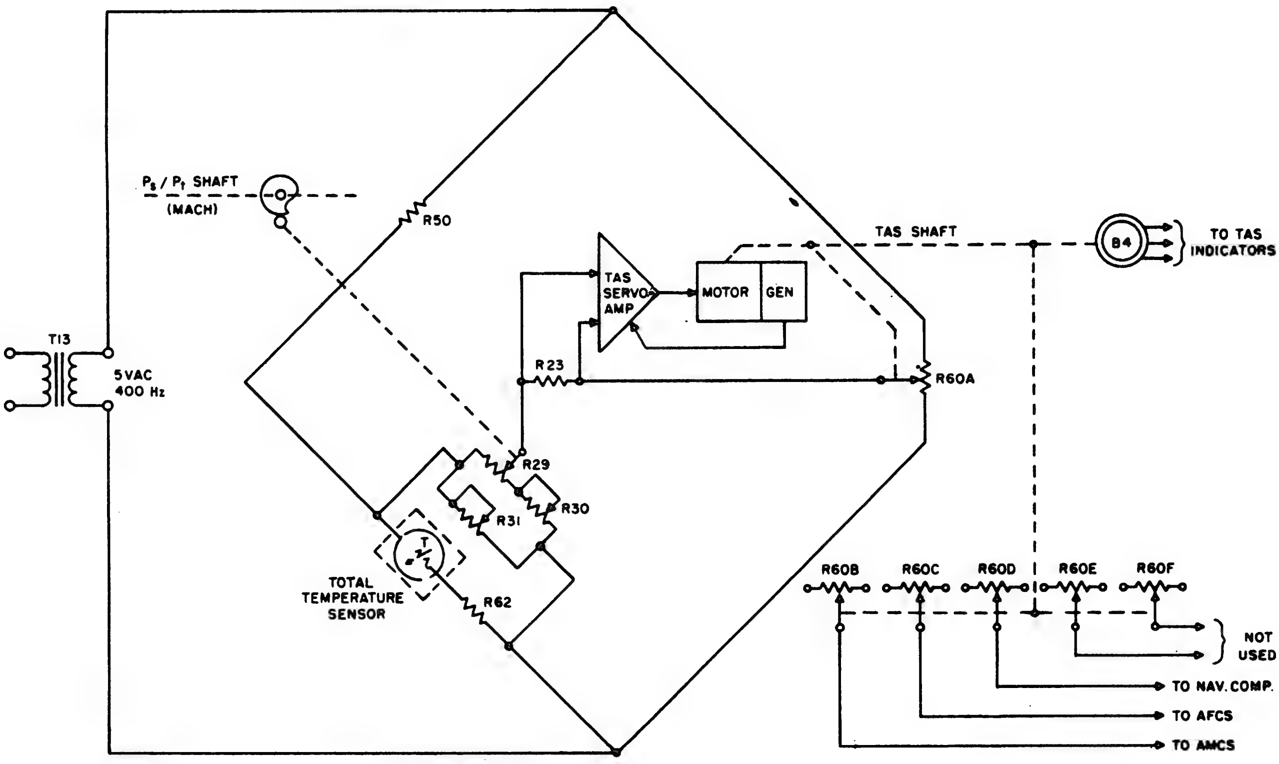

Figure 7-12.—Functional diagram of TAS shaft mechanization.

the potentiometer assembly, which are used by the AFCS.

Mach Switches

Mach switches S9 and S10 are actuated by their associated Mach function cams. The switches are set to open and close at specific Mach numbers.

Mach Error Output

Mach error output information to the AFCS is transmitted by the rotor of synchro transmitter B3 which is connected to the Ps/Pt shaft through L8, the electromechanical clutch. When MACH HOLD is selected at the AFCS, the clutch engages and any movement of the Ps/Pt shaft shall rotate the synchro rotor. The electrical synchro output signal will indicate any Mach deviation from the engage reference.

ORGANIZATIONAL LEVEL PERFORMANCE TESTS

Maintaining the ADCS at the organizational maintenance level is limited to checking the operation of the system, isolating the fault, and correcting the fault by replacing faulty line replacement units or by repairing interconnecting lines and connections. Modular repair of the ADC is done by the intermediate level maintenance activity; such repairs are beyond the scope of this manual.

TEST EQUIPMENT USED FOR PERFORMANCE TESTS

In order to make performance tests on the air data computer set, a variety of portable line testers, simulators, and equipments are utilized. Primarily, the line testers consist of pneumatic testers for supplying pitot and static inputs, a high pressure dry air source as a substitution for engine bleed air, an electrical test set which

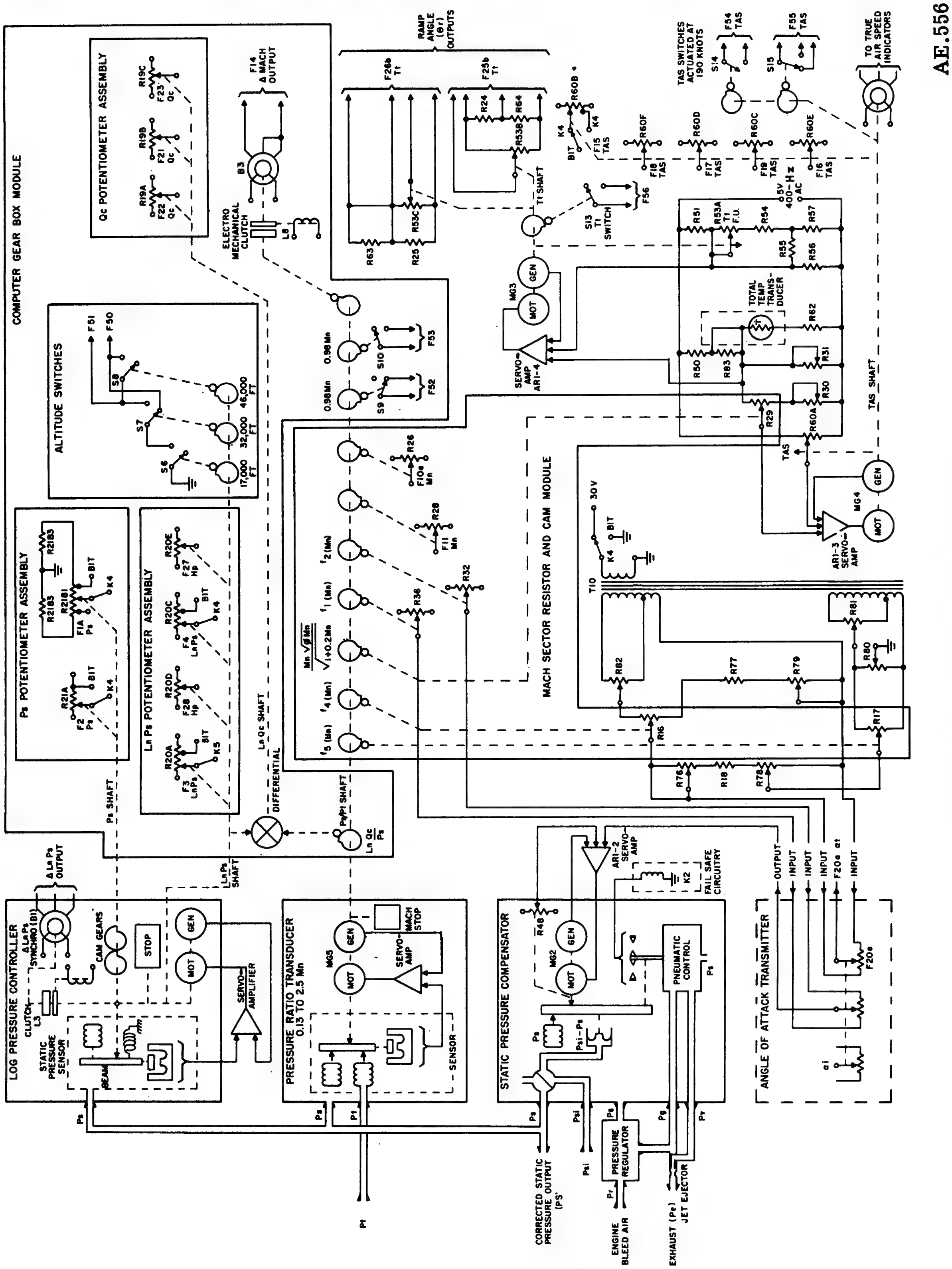

Figure 7-13.—ADC block diagram.

Table 7-2.—Mach potentiometer functions.

Item No.	Function
R16 R17	Used to supply Mach number correction to the true angle-of-attack output circuit.
R26	Output 10a schedules the yaw rate signal to the flight control group for Mach number.
R28	Output 11 schedules the signal from output number 9 with Mach number, to furnish the flight control group with an altitude hold signal.
R29	Used to supply Mach information to the true airspeed servoamplifier.
R32 R36	Used to supply two functions of Mach number to be used in conjunction with the angle-of-attack transmitter potentiometer C to supply correction information to the SPC.

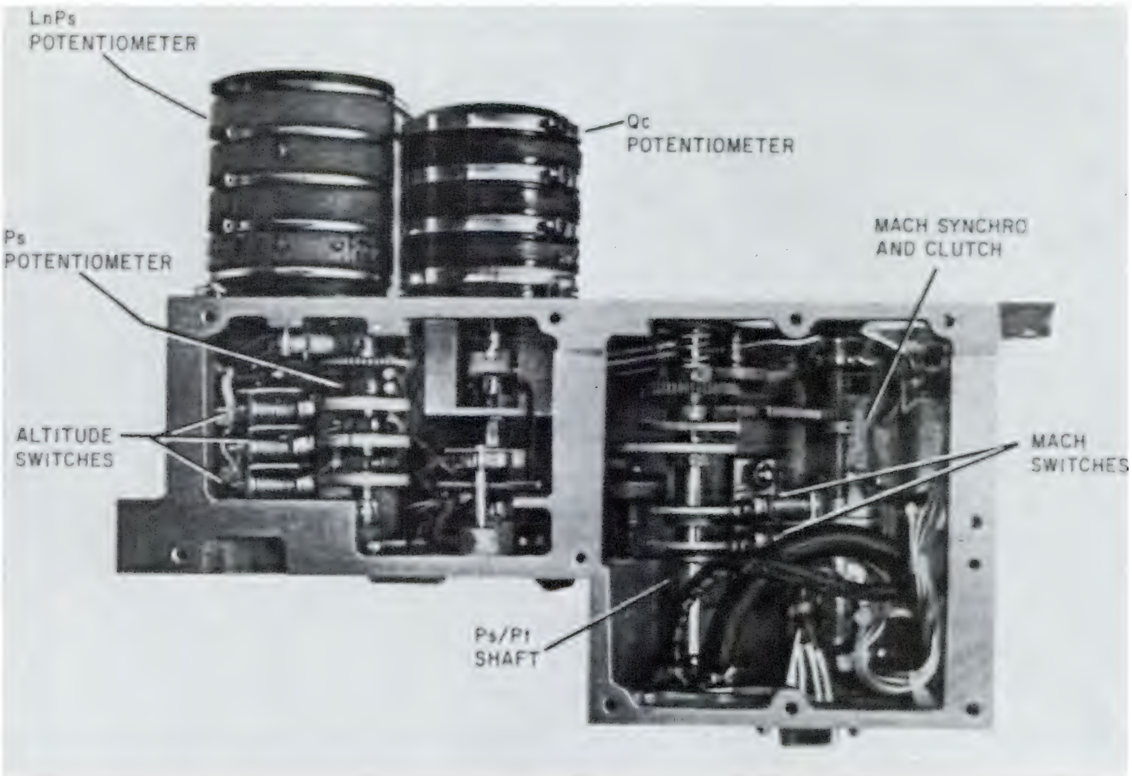

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Figure 7-14.--ADC gearbox module.

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Figure 7-15.—Pneumatic Test Set VPT-10F-11072S.

simulates the various computer functions for checking computer potentiometer outputs, a true airspeed tester for checking the true airspeed portion of the computer set and indicators, etc. There are a number of different types of electrical and pneumatic line testers that are interchangeable on some aircraft models while other aircraft models specify particular line testers to be used. Therefore, it is necessary to check the appropriate Maintenance Instructions Manual in order to determine the proper testers to be used.

Since there are some duplications in line testers, only one tester of each general category is discussed in this manual.

Pneumatic Tester VPT-10

The VPT-10 pneumatic test set (fig. 7-15) is the most common pneumatic tester used in performing tests on the pneumatic portion of the air data computer. It supplies pitot and static pressure inputs to the computer for simulating various altitudes and airspeeds. It is also used to perform leak tests in the computer and the aircraft pitot-static system.

Electrical Tester AN/ASM-62

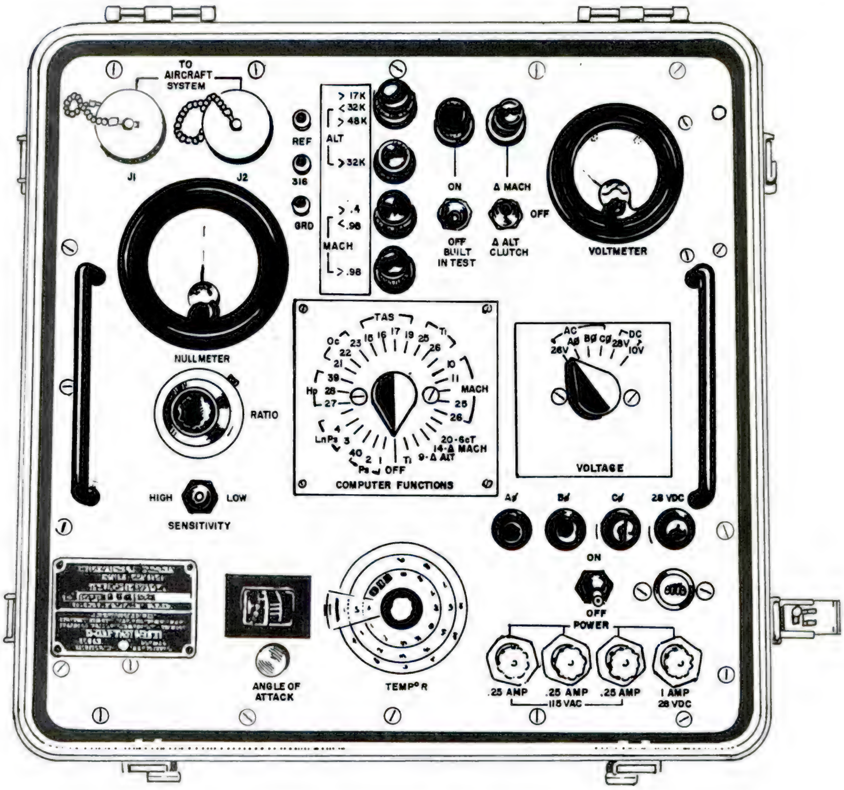
The Air Data Computer Test Set AN/ASM-62 (fig. 7-16) is used in conjunction with the pneumatic tester for checking the computer potentiometer outputs. It tests the computer functions for various specified input data of angle of attack, absolute temperature, airspeed, and altitude.

TEST PROCEDURES

In performing functional tests on the air data computer, refer to the appropriate maintenance data for the aircraft, model, and aircraft configuration of the aircraft on which the tests are to be performed. Follow the proper test sequence as is given in the maintenance test data and correct each fault before proceeding to the next test. In general, the proper order of functional tests begins with a pneumatic leak test, then work through all the potentiometer and switch checks, and finish with the static pressure compensator check.

NOTE: When performing the static pressure compensator check, use an external source of pneumatic pressure 150 to 3,000 psi of clean, dry air.

Figure 7-17 shows a typical pneumatic test hookup on an F-4 aircraft, and figure 7-18 shows the hookup for the Air Data Test Set, AN/ASM-62.



AIR DATA COMPUTER TEST SET TS-1689/ASM-62

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Figure 7-16.—Air Data Computer Test Set AN/ASM-62.

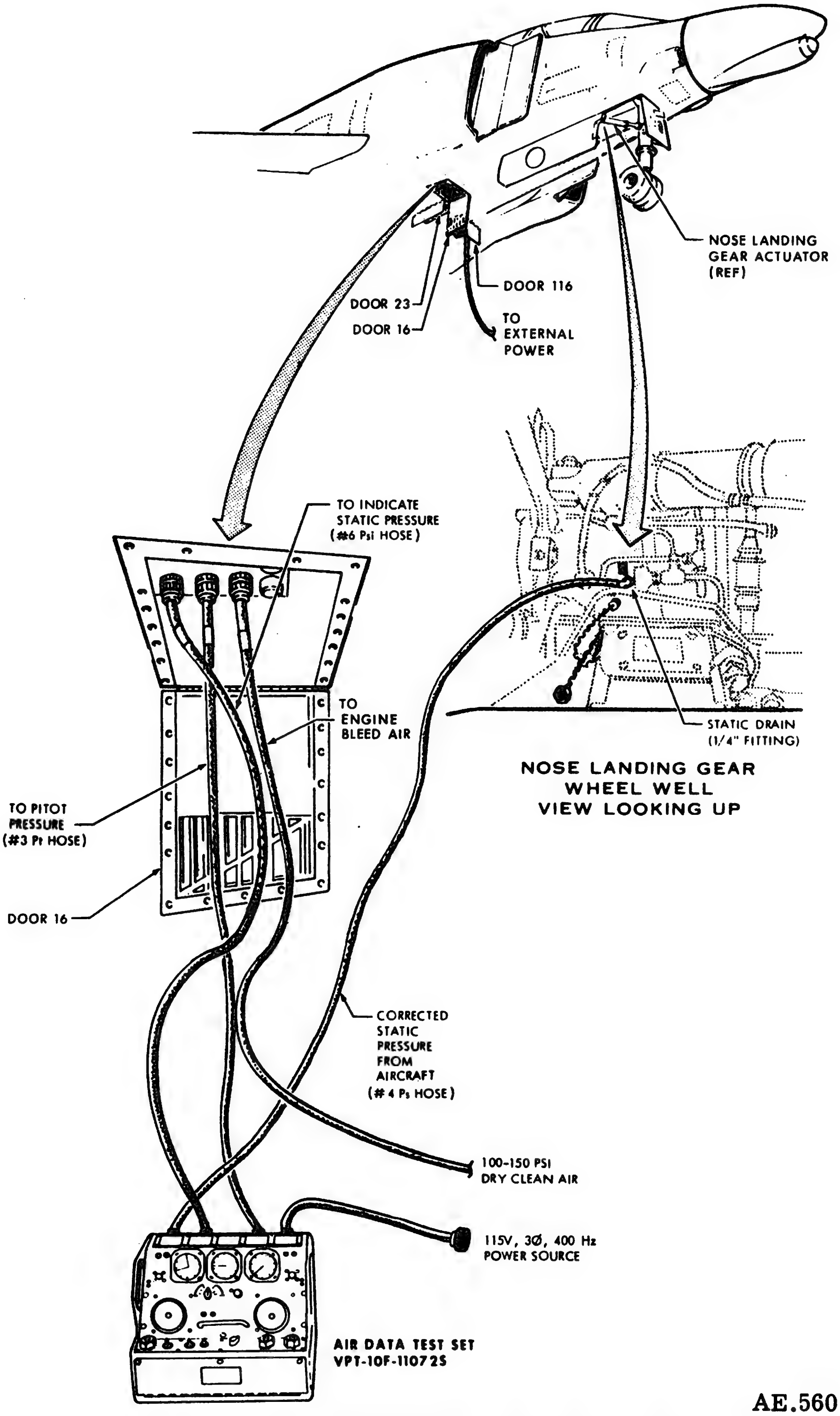

Figure 7-17.—Test equipment pneumatic hookup.

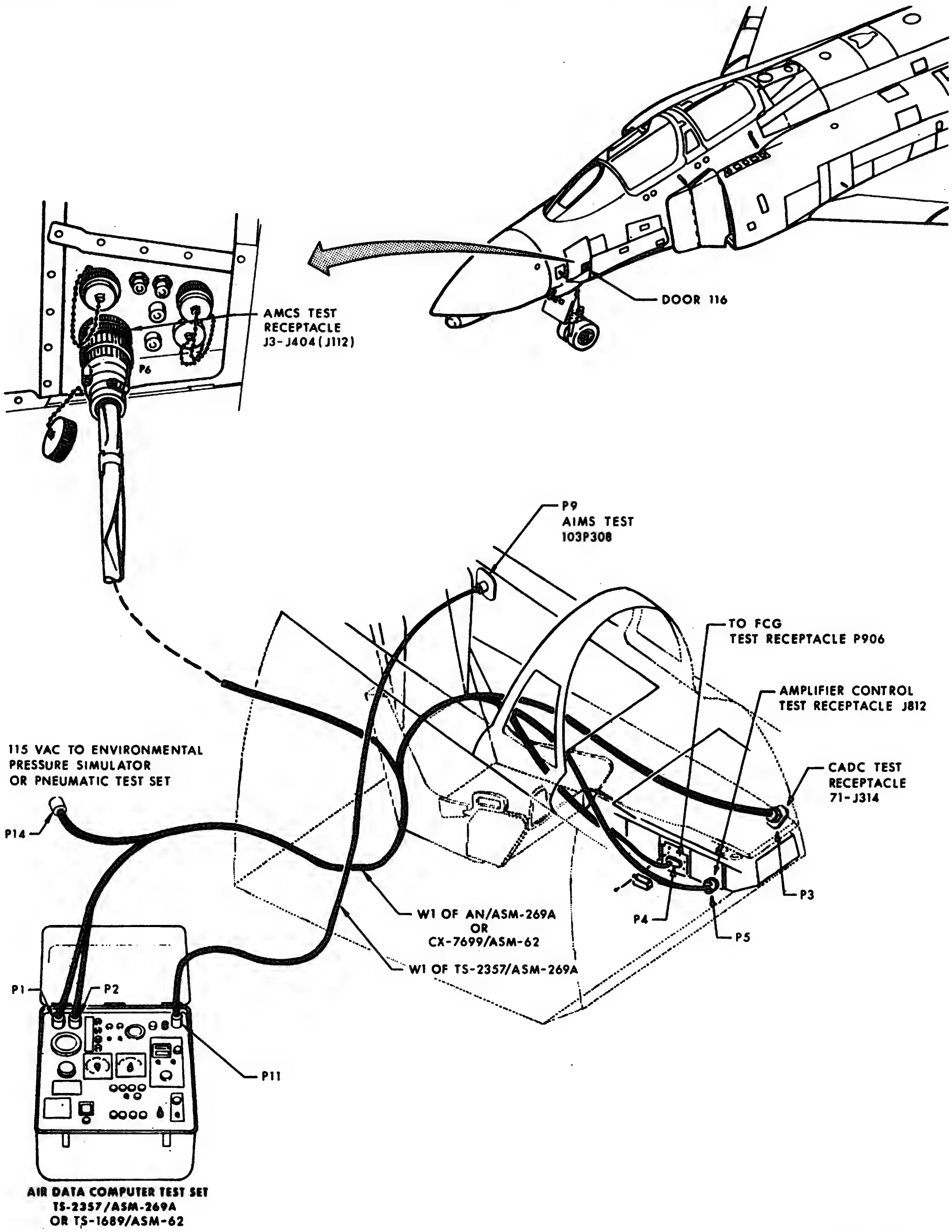

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Figure 7-18.—Air Data Test Set AN/ASM-62 hookup.

CHAPTER 8

AIRCRAFT COMPASS SYSTEMS

The development of aircraft compasses and compass systems has progressed from the direct reading magnetic compass (a long-term directional indicator) and the directional gyro (a short-term directional indicator) to the heading indicating system commonly used in aircraft today—the compass-controlled directional gyro.

The compass-controlled directional gyro system is a heading indicating system designed to combine the desired features of the magnetic compass and the directional gyro and, at the same time, to minimize the undesirable effects of the directional gyro and the magnetic compass.

Some of the errors inherent in the magnetic compass are (1) deviation errors, (2) turning errors, (3) aircraft attitude and speed change errors, and (4) errors resulting from a weak horizontal component of the earth's magnetic field.

Deviation errors are minimized by locating the magnetic compass transmitter (flux valve) at a point in the aircraft of least deviation effects—tail or wingtip—and further reducing these errors by compensating the transmitter. The remaining errors, although still present in the transmitter, are absorbed by the stability of the heading system's directional gyro.

The directional gyro—the heart of the compass system—is subject to errors of its own that, if not corrected, limit the system's usefulness in those areas where the magnetic compass is unreliable. Unreliable areas are the magnetic poles where the horizontal component of the earth's magnetic field is weak and where the earth's field is distorted by large ferromagnetic deposits.

Errors inherent in the directional gyro are drift and apparent drift; the sum of the two is the total drift of the directional gyro.

The drift error of the directional gyro arises from slight imperfections in dynamic balance and from bearing friction; these result in small torques being impressed upon the gyro. Since it is practically impossible to manufacture perfect gyroscopes, it is also equally difficult to manufacture gyroscopes of identical drift characteristics. Furthermore, the drift rate will vary as the relative position of the gyro spin axis and its gimbals vary. However, an average drift rate can be determined for each gyro by the manufacturer that will enable the maintenance man to provide necessary compensation. Compensating for gyro drift will not eliminate all gyro drift; it will reduce the drift and vary the remaining drift about a zero reference. Drift compensating data is furnished by the manufacturer and adjustment is made in the compass amplifier upon installation of the directional gyro. When compensation adjustments have been made, a voltage is impressed on the directional gyro azimuth torquers that is sufficient to produce a torque of equal magnitude and in opposition to the average torque which caused the gyro to drift.

Apparent drift of a directional gyro is not a drift of the gyro itself; it is the movement of the gyro case about the gyro (the gyro remaining fixed in inertial space). Due to the earth's rotation (counterclockwise as viewed in northern latitudes and clockwise in southern latitudes), the directional gyro will cause a repeater indicator to rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The rate of case drift varies from 15° per hour at the poles where the vertical axis (output axis) of the directional gyro is parallel to the earth's spin axis to zero at the Equator where the vertical axis of the directional gyro is perpendicular to the earth's spin axis. The rate of case drift at latitudes between the Equator and the poles is 15° per hour times the sine of the latitude. Therefore, to compensate for apparent drift, the voltage supplied to the azimuth torquers is sufficient to produce a torque equal in magnitude and in opposite direction to the apparent drift at local latitudes. Apparent drift compensation precesses the gyro so that its spin axis maintains its position relative to the case during level flight and with no change in course.

With drift and apparent drift compensation features of the compass-controlled directional

gyro system, there is still gyro drift that occurs during flight which cannot be entirely eliminated. For this reason, the mode of operation most used is compass slaving where the directional gyro acts as a magnetic heading stabilizer.

Compass-controlled directional gyro systems discussed in this chapter are the MA-1 and the MF-1. The features of the MA-1 compass system are discussed in detail, while only those features of the MF-1 compass system that differ from the MA-1 compass system are covered in this chapter.

The MA-1 compass system is manufactured by Lear and General Electric. Both companies produce compass systems that achieve practically the same end result, but the methods and features used in their systems differ slightly. Their differences are discussed only if it is considered that it will not disturb the continuity of the subject matter.

MA-1 COMPASS SYSTEM

TRANSMITTERS

Basically, the transmitters used in the different MA-1 compass systems are the same except for the nomenclature and appearance. Their theory of operation is the same. Figure 8-1 (A) shows a typical compass transmitter; figure 8-1 (B) is an internal schematic diagram of the transmitter.

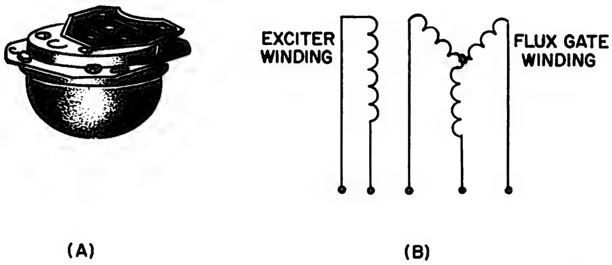

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Figure 8-1.—(A) Typical compass transmitter; (B) schematic of compass transmitter.

The compass transmitter is an inductor type. It senses the magnetic heading of the aircraft and generates a corresponding signal. The transmitter is only a few inches in height, and can be installed within the wing or tail of the aircraft where magnetic disturbances are lowest. The compass transmitter consists of a hemispherical bowl which contains the sensing element. This element is mounted pendulously so that its average position in the horizontal component of the earth's magnetic field is maintained. To prevent excessive swinging of the functioning element while the aircraft is in flight, the hemispherical bowl is filled with damping fluid and the functioning element is weighted so that it can, within limitations, continually respond to the force of gravity.

The compensating screws, located on top of the transmitter, are used to eliminate most of the magnetic deviation caused by the aircraft electrical equipment and ferrous metal. One of the two compensating screws is lettered N-S for north and south deviation correction, the other E-W for east and west correction.

The core (exciter) of the compass element is periodically saturated with a 400-hertz a-c source. The combination of the saturating flux and the earth's field flux combine to produce a resultant flux of twice the frequency (800-hertz) of the saturating flux. The resultant flux induces a resultant voltage into the stator (flux valve winding) which becomes the azimuth information for the directional gyro.

DIRECTIONAL GYRO UNIT

Every MA-1 compass system employs a directional gyro unit. These directional gyro units are basically the same. Figure 8-2 shows two directional gyro units. Their functions are the same, but they are used in two different MA-1 compass systems.

The directional gyro shown in figure 8-2 (A) is a separate unit; the gyro shown in figure 8-2 (B) is contained inside an amplifier unit. The internal appearance of both directional gyro units is basically the same; therefore, only the directional gyro shown in figure 8-2 (A) is discussed. It consists of a gyro motor mounted in a gimbal suspension, torque motors for slaving and leveling, and pickoffs to provide signals containing leveling and azimuth information. The gimbal suspension consists of an inner gimbal and an outer gimbal arranged so that the gyro has three independent axes of rotation. The motor is a synchronous hysteresis type and operates at a speed of 24,000 rpm. The complete gyro is hermetically sealed in inert gas at a pressure of one atmosphere.

Figure 8-3 shows the directional gyro unit motor in gimbal suspension. A cutaway view of

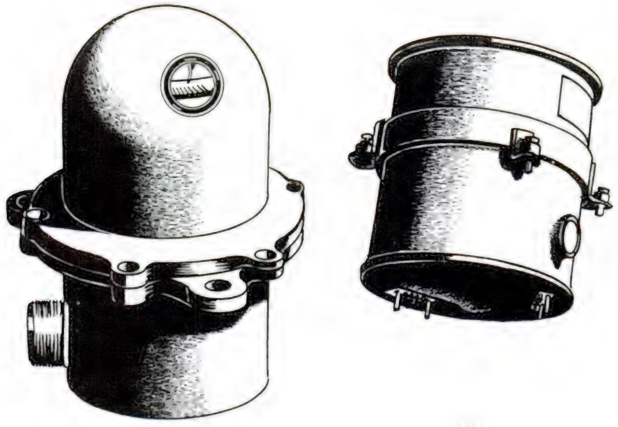

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Figure 8-2.—Directional gyro units.

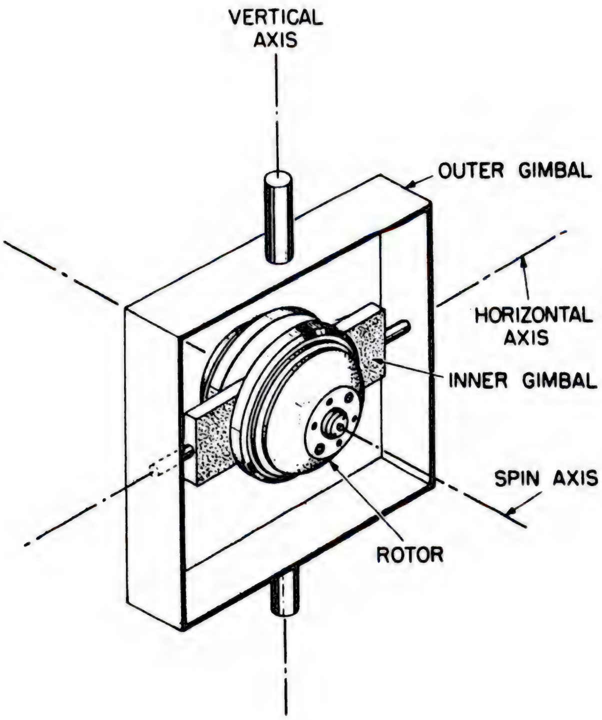

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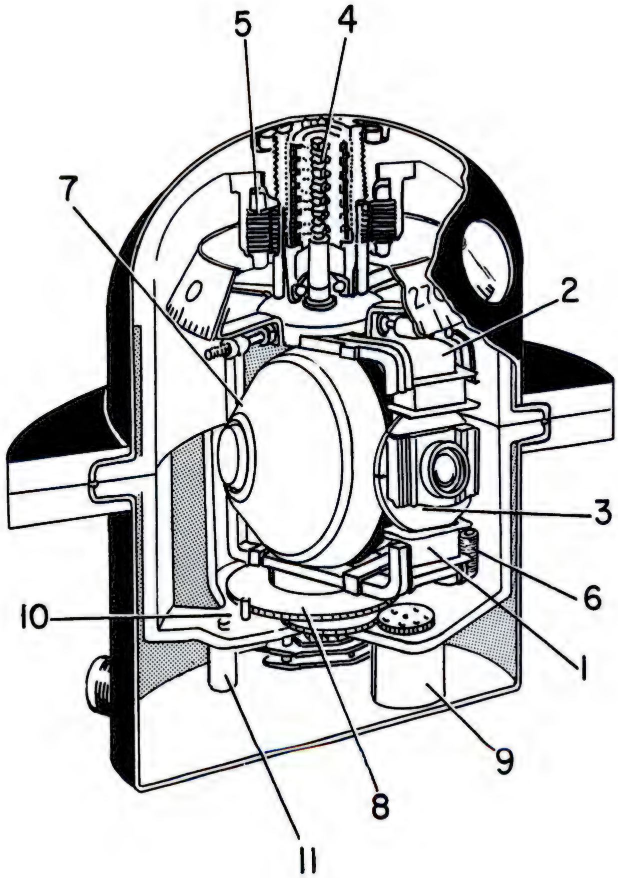
Figure 8-3.—Directional gyro unit motor in gimbal suspension.

the complete gyro unit is shown in figure 8-4, and the electrical schematic of the gyro unit is shown in figure 8-5.



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1. Slaving torque motor coil.
2. Outer gimbal.
3. Magnet.
4. Brushes.
5. Leveling torque motor.
6. Leveling pickoff coil.
7. Gyro motor.
8. Gear.
9. Synchro transmitter.
10. Antispin assembly.
11. Antispin motor.

Figure 8-4.—Cutaway view of a directional gyro unit.

Slaving Torque Motor

The slaving torque motor (1, fig. 8-4) consists of two sets of coils mounted on the outer

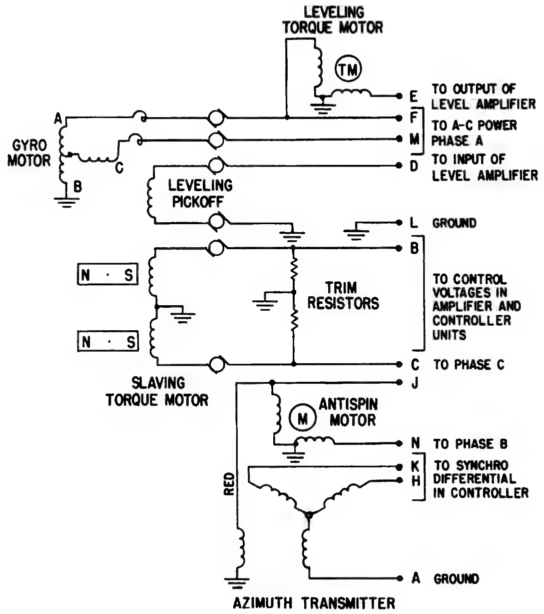

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Figure 8-5.—Circuit diagram of a directional gyro unit.

gimbal (2) and two disk-shaped permanent magnets (3) mounted on the inner gimbal. When the coils are energized by a direct current, their magnetic fields react with the fields of the magnets on the inner gimbal to produce a torque about the horizontal axis. This torque processes the gyro about the vertical axis. The direction of precession is dependent upon the polarity of the direct current applied to the coils. Electric connections between the inner and outer gimbals are made through low torque spiral hairsprings (brushes) (4).

The slaving torque motor receives current from either the fluxvalve transmitter or latitude error signal controller, but NOT from both at the same time.

Leveling Torque Motor

The leveling torque motor (5, fig. 8-4) consists of a 2-phase stator mounted on the case frame and a hysteresis rotor mounted on the outer gimbal. The excitation winding of the stator is energized at all times with 115-volt, 400-hertz, single-phase power. The 400-hertz single-phase voltage to the control winding is derived from the leveling amplifier output. This voltage varies from 0 to 26 volts, depending upon the amount of leveling required, and shifts in phase 180°, depending on the direction of leveling required. When the control winding is energized, a torque is exerted about the vertical axis, causing the gyro to precess about the horizontal axis.

Leveling Pickoff

The leveling pickoff is taken from two coils (6, fig. 8-4) mounted on the outer gimbal. These coils are linked by the stray magnetic flux from the stator of the gyro motor (7). The induced voltage in these coils is minimum when the gyro spin axis is perpendicular to the vertical axis. When the gyro motor spin axis tilts about the horizontal axis, an a-c voltage is induced into the pickoff coils. The magnitude of the induced voltage is a function of the angle of tilt, and the phase is a function to the direction of the tilt.

Azimuth Information

A large gear (8, fig. 8-4) at the bottom of the gyro's outer gimbal is coupled to the rotor of the synchro transmitter (9) which provides an electrical output signal. The output signal is a function of the position of the gyro in azimuth.

The signals from the gyro synchro transmitter are fed through a synchro differential (located in the controller unit) and a synchro control transformer (located in the amplifier unit) to the servoamplifier. The output signals from the servoamplifier drive the servomotor that positions the rotors of three synchros. These rotors are mechanically coupled to the servomotor shaft. The output of one of these three synchros provides azimuth information for the autopilot or other navigational equipment. This is discussed in detail later in the chapter.

Antispin Assembly

An antispin assembly (10, fig. 8-4) is employed in the gyro unit to prevent gyro nutation during starting and shutdown.

The antispin assembly consists of a spring-loaded pin that presses against the edge of a gear on the outer gimbal. Ten seconds after the gyro is energized, the antispin motor (11)

moves the pin away from the gear so that the outer gimbal is free to rotate. When the gyro is deenergized, the pin immediately moves against the gear, applying a braking action to the outer gimbal.

Electrical Connections

Electrical connections for the gyro motor, the slaving torque motor, and the leveling pick-offs are made through brushes and sliprings at the top of the outer gimbal.

COMPASS CONTROLLER

The compass controller contains controls for synchronizing the compass system, selecting the mode of operation, and setting latitude compensation. Figure 8-6 shows two typical controller units. Figure 8-7 is a schematic of the controller shown in figure 8-6 (B).

The two controllers shown in figure 8-6 are identical in operation but differ slightly in appearance. For purposes of explanation, the General Electric controller is described.

Synchronizing Procedure

The heading set knob (labeled PULL TO SET on the controller) in figure 8-7 permits rotation of the synchro differential rotor, S4. This synchro is connected between S5 (the output synchro of the gyro) and S1 (the synchro control transformer in the amplifier). This

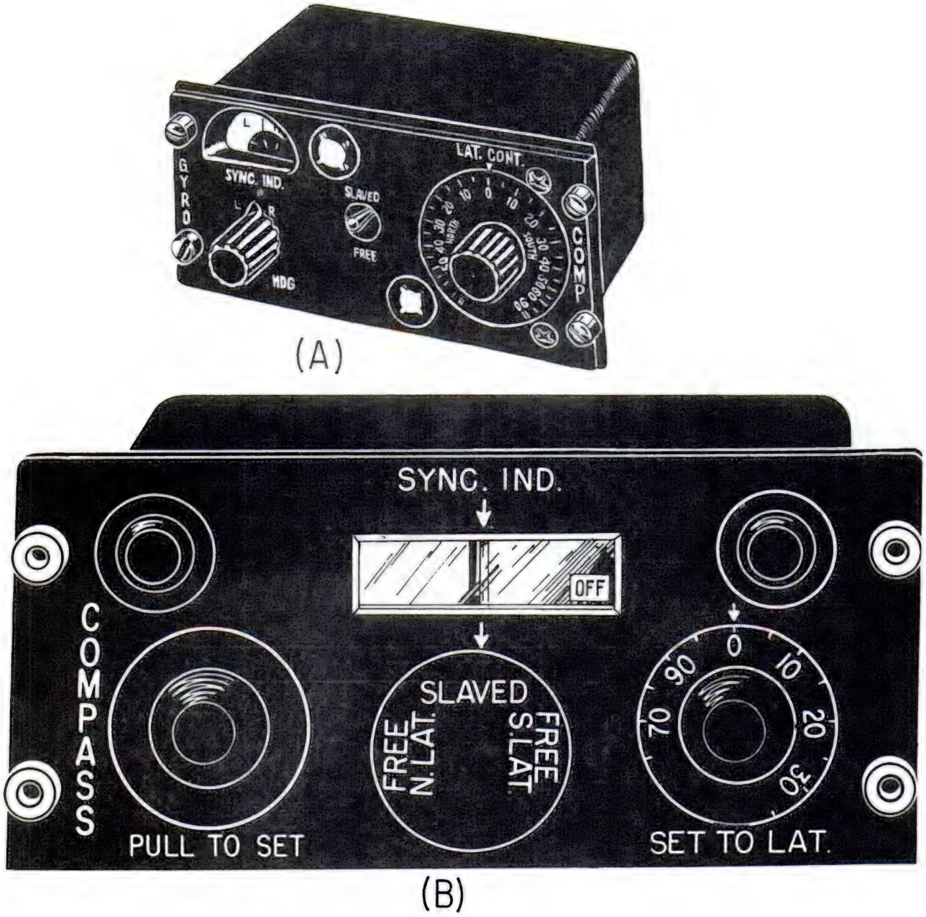

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Figure 8-6.—(A) Lear MA-1 controller; (B) General Electric MA-1 controller.

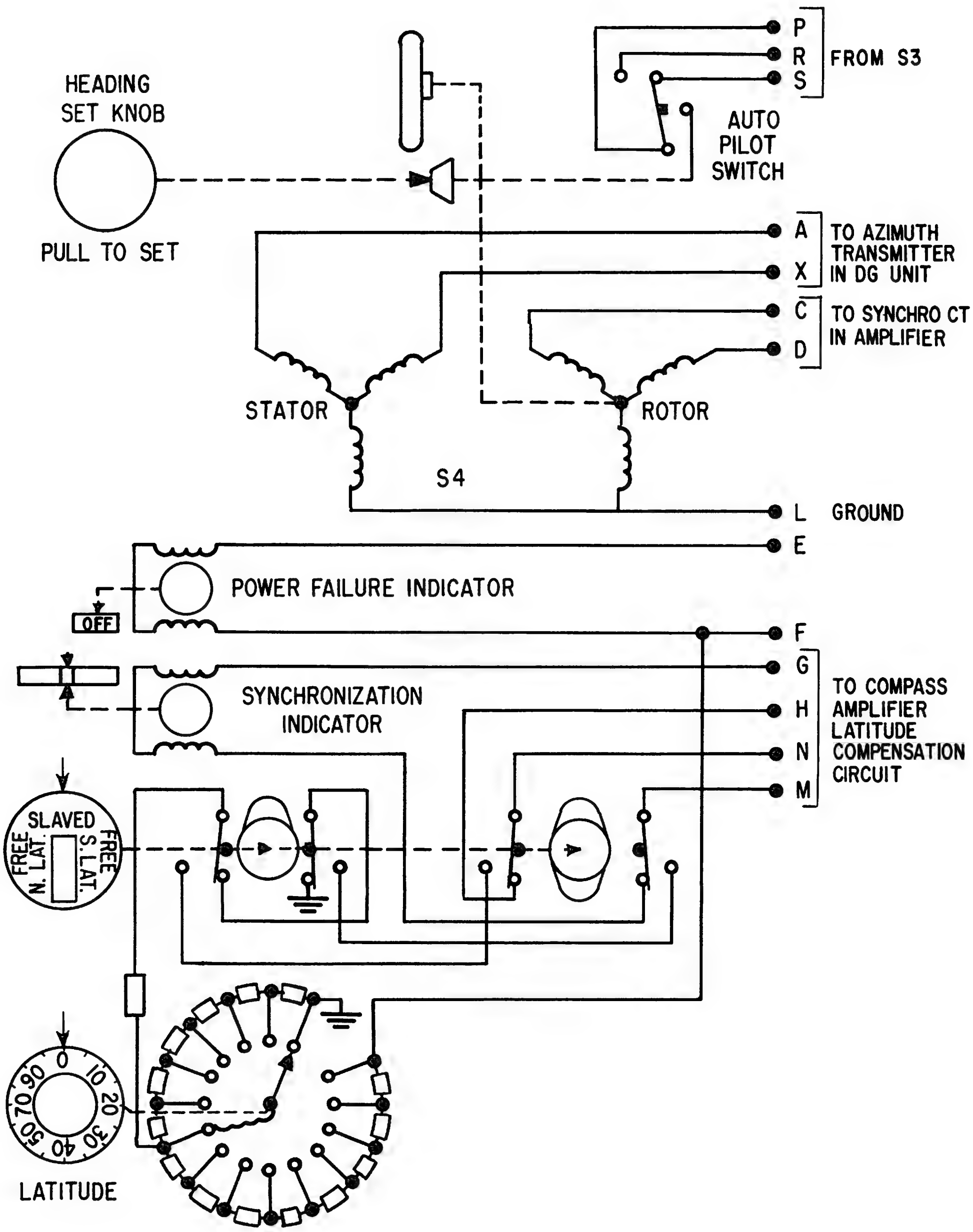

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Figure 8-7.—Circuit diagram of the General Electric controller.

arrangement makes it possible to change the position of the servo shaft without actually moving the gyro axis.

In order to understand the importance and need for the synchro differential, it is necessary to analyze what happens after the compass system is turned on. Assume that the gyro is up to speed, and its axis is as shown in the right-hand section of figure 8-8. Also assume that the fluxvalve compass is delivering directional information as shown at synchro S2 in the left-hand section of the figure.

Beginning with these conditions, the following events occur:

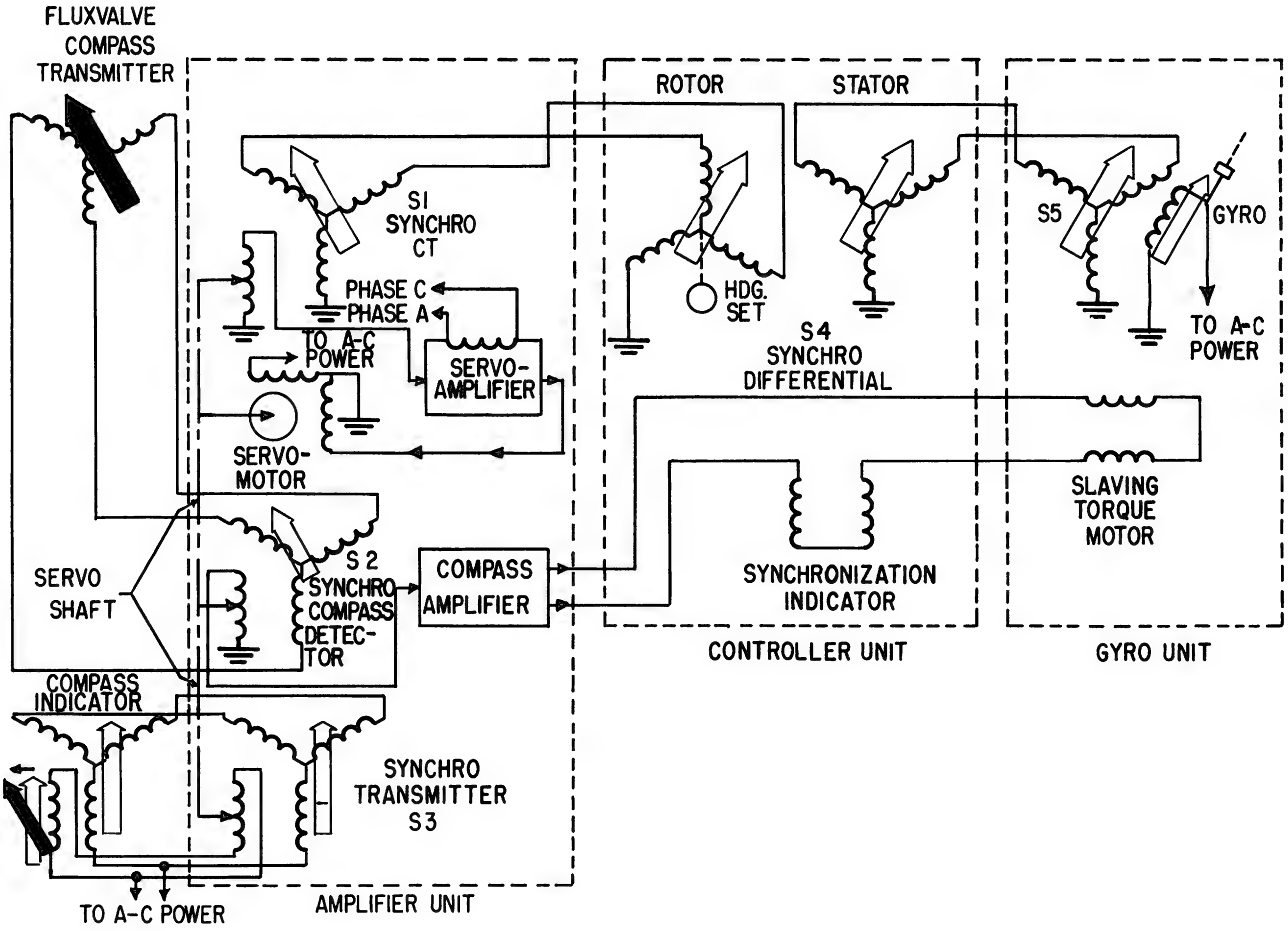

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Figure 8-8.—Circuit diagram of the General Electric controller.

1. As soon as power is applied, the rotor of synchro S1 (control transformer) delivers a signal to the servoamplifier due to the angular difference between the stator field and rotor. The magnitude of this signal is proportional to the angular error.

2. Depending upon the phase characteristics of the input signal to the servoamplifier, the output signal is such that it drives the servomotor in the direction which reduces the error voltage. Its rotation continues until the rotor of the CT is alined with the field of the CT's stator.

3. Since the synchro compass detector's rotor and the synchro transmitter's rotor are connected to the same servo shaft, they too assume the same directional position as the rotor of the synchro CT.

4. At the same time that events 1, 2, and 3 are occurring, the synchro compass detector's rotor will sense an angular difference between itself and the synchro stator and feed a signal into the compass amplifier. The phase and magnitude of this signal is proportional to the size and direction of the angular error between the stator field and rotor.

5. The output signal from the compass amplifier drives the slaving torque motor in a direction to cause the gyro's axis to precess in an attempt to aline the gyro synchro S5 with the directional information being received from the fluxvalve compass transmitter. However, this

precession takes place at a rate of approximately 2° per minute. The synchro CT and the servoamplifier, on the other hand, are designed so that the servo shaft will position itself almost instantly when the field of the synchro stator S1 changes direction. If the angular difference between the magnetic heading S2 and the gyro position heading S5 were 90°, it would obviously take 45 minutes for them to synchronize. The synchro differential S4 located in the controller unit is used to reduce this synchronizing time to a few seconds. This is done in the following way:

The heading set knob (fig. 8-8), which is mechanically connected to the rotor of the synchro differential S4, is rotated to position the rotor so that the direction of the field produced in the stator of the synchro is CT (S1) is identical to that of the fluxvalve which is on the stator of the compass detector synchro S2. Therefore, the rotor of the synchro CT (S1) and the rotor of the compass detector synchro CT (S2) will be positioned perpendicular to the stator fields.

At this time there will be no signal to either the servoamplifier or the compass amplifier. The rotor synchro transmitter S3 will be positioned in alinement with the flux field and adjusted gyro field. The signal induced in the stator of the synchro transmitter S3 is repeated on the stator of the compass indicator (RMI) which now indicates the gyro stabilized magnetic heading of the aircraft.

As a result of changing the rotor's position in the synchro differential, the rotor of the synchro compass detector is positioned so that it is practically alined in the same direction as the stator field. Thus, the signal being fed into the compass amplifier is extremely small. The output signal of the compass amplifier is also very small. However, this small remaining signal is sufficient to precess the gyro until the rotor and stator field of S2 are completely alined.

The Lear compass controller differs from the General Electric compass controller in that the Lear controller employs a fast slave feature for synchronizing the compass system. The SET HDG switch on the Lear controller allows a RIGHT or LEFT selection, so that when either is selected the compass amplifier is disconnected and a higher voltage is connected to the azimuth torquers which slaves the gyro at a much higher rate than normal. The fast slaving voltage is applied as long as the SET HDG switch is in a slaving position; therefore, it must be returned to the center position when the gyro has reached "sync" position.

Synchronization Indicator

To facilitate synchronizing the MA-1 compass system by means of the synchro differential, a SYNC indicator (a zero center milliammeter) is installed in the controller. (See fig. 8-6.) When the vertical white marker in the indicator is approximately centered, it shows that the output signal from the compass amplifier is near null and that synchronization exists between the fluxvalve compass and gyro.

After synchronization is achieved, the gyro is then slaved to the fluxvalve compass and its axis is precessed in response to any average directional changes in the fluxvalve compass. Since the gyro, when slaved, precesses at such a slow rate (2° per minute), it does not respond to the continuous rapid fluctuations of the fluxvalve compass, but only to the average direction changes.

Autopilot Switch

An autopilot switch is connected to the heading set knob so that the switch is energized when the knob is pulled out. This switch can be used to cut out the autopilot when the system heading is being changed. It is used only when signals from S3, the servo output synchro of the system, are used for autopilot operation (fig. 8-7).

The mode of operation selector switch, labeled FREE N LAT—FREE S LAT (fig. 8-7), selects either compass controlled (slaved) or free gyro operation. There are two switch positions for free gyro operation—one for northern latitudes, and one for southern latitudes.

Latitude Compensation

The latitude compensation control is located at the right-hand side of the controller unit. One is labeled SET TO LAT and the other LAT CONT (fig. 8-6). This control sets the amount of compensation voltage required for canceling the apparent drift due to the earth's rotation. This compensation voltage, which is used only when the system is set for free gyro operation, provides a direct current to the coils of the slaving torque motor of the gyro. This current produces a torque which precesses the gyro at

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Figure 8-10.--Block diagram of amplifier, controller, and gyro unit.

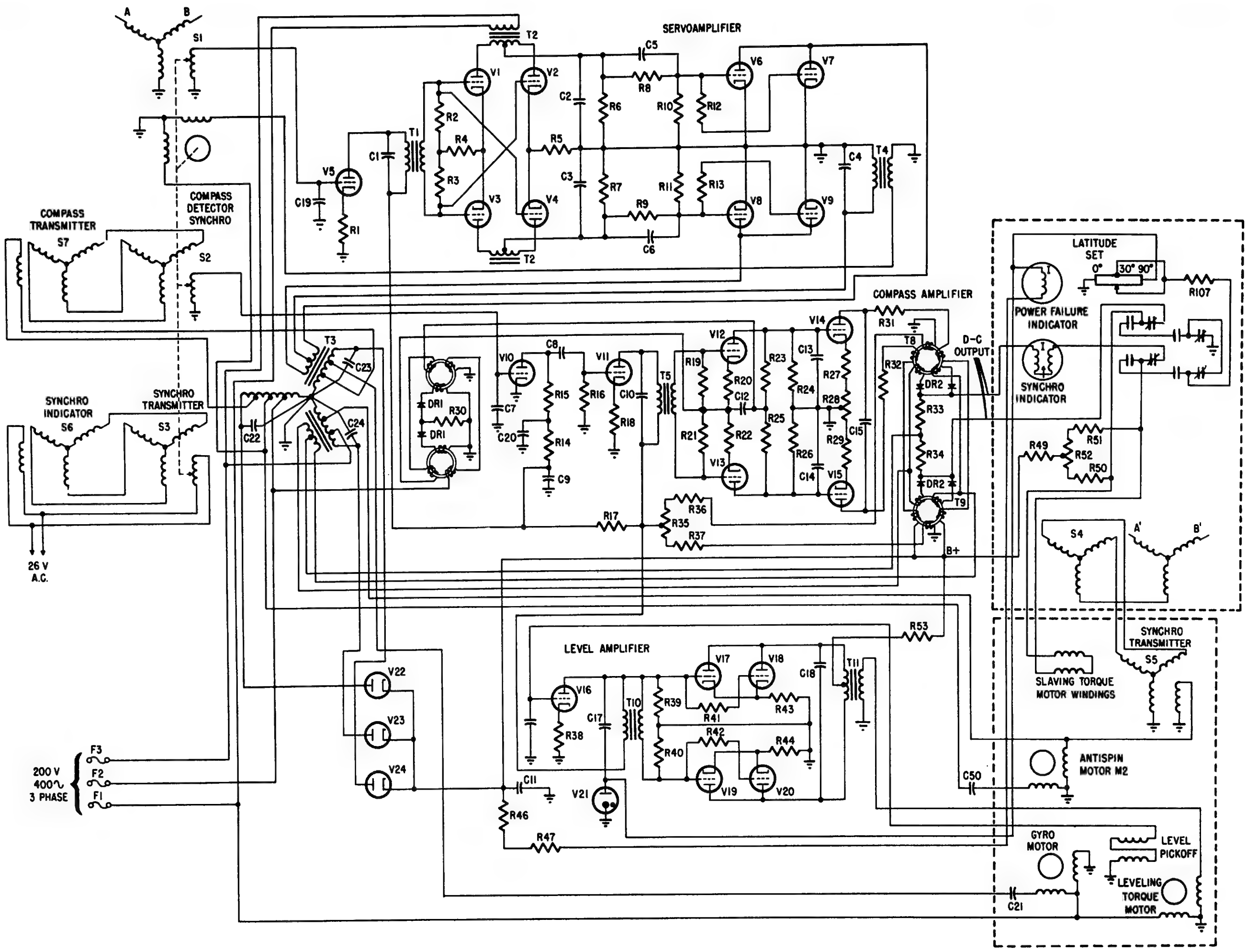

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Figure 8-11.—Overall schematic of the General Electric MA-1 compass system.

not bypassed. This feature tends to maintain the output signals from the servoamplifier relatively uniform in magnitude, regardless of the size of the error input signals.

Since V1, V2, V3, and V4 become saturated when the error signals become greater than 1°, the torque delivered by the servomotor for error signals of 1° would be almost exactly the same as for strong error signals.

Phase Discriminator Operation

When no signal is applied to the discriminator circuit (fig. 8-12), tubes V1 and V2 conduct alternately and thus develop a small voltage across R6. Likewise, V3 and V4 develop a voltage across R7. The d-c voltages across R6 and R7 are fed through a filtering and stabilizing network to the grids of the output tubes V6, V7, V8, and V9.

The plates of the output tubes are excited 180° out of phase by a 400-hertz voltage from the phase A transformer. The amplifier output, which is produced between the center tap of the plate winding on the power transformer T3 and ground, is coupled to the secondary of T4, and in turn is fed to the control phase of the servomotor M1. The excitation winding of M1 is powered by phase C. Since the grid signals are negative and of the same magnitude,

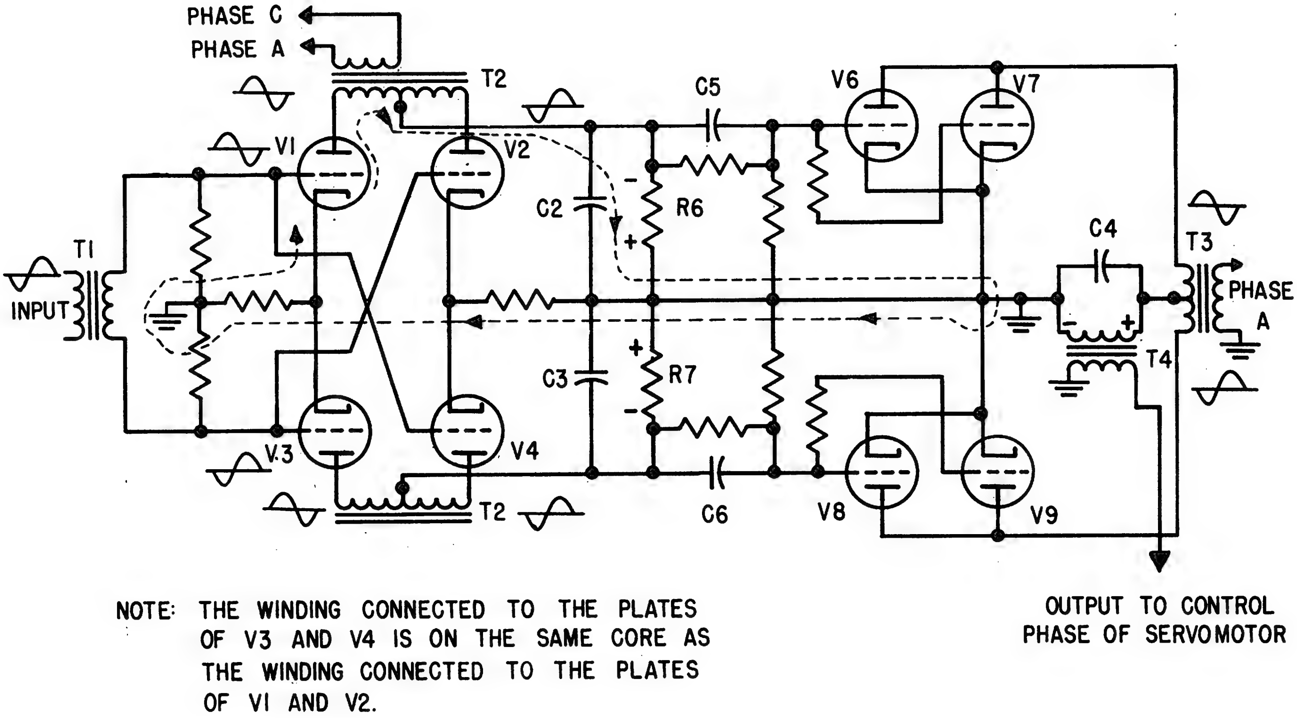

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Figure 8-12.—Phase discriminator in servoamplifier unit.

power amplifiers V6, V7, V8, and V9 conduct equally, and thus develop a small output voltage during the first half cycle that is equal in magnitude and polarity to the voltage developed during the second half cycle in the secondary of T4. This is shown in figure 8-13 (C). Due to the filtering action of C4, the resultant waveshape has a frequency of 800 hertz.

Since the voltages developed during each half cycle are equal in magnitude, there is no turning torque produced in the servomotor when this 800-hertz signal is applied to its control winding.

Referring again to figure 8-12, assume that the output signal from T1 is fed to the grids of V1 and V3 with the phase polarity as shown, and that the line-to-line reference voltage taken from phase A to phase C induces a voltage in the secondary and tertiary windings of T2 as shown. During the first half cycle of signal voltage, the only tube whose grid and plate are both going positive simultaneously is V1. Therefore, V1 conducts, and a relatively large voltage is developed across R6 as shown by the dashed waveform in figure 8-13 (B). During the second half cycle, the grid and plate of V2 go positive simultaneously, thus causing this tube to conduct. Again a voltage is developed across R6 with the same polarity as the previous pulse. The resultant output signal resembles that of a full-wave rectifier. Capacitor C2 smooths out this d-c voltage as shown by the solid line in figure 8-13 (B).

Referring to tubes V3 and V4, when the plate of V3 is positive, the input signal on its grid is negative and therefore conducts less than during no-signal conditions. Likewise, V4 conducts less during the second half cycle. Therefore, the d-c signal developed across R7 is less than during no-signal conditions, and thus the input signal to V8 and V9 is less negative.

Assume that the secondary voltage of power transformer T3 (phase A) is as shown in figure 8-12. Since the input d-c signal to tubes V6 and V7 is very negative, they conduct less than during no-signal conditions. On the other hand V8 and V9 conduct more heavily whenever their plates are positive, which in this case is

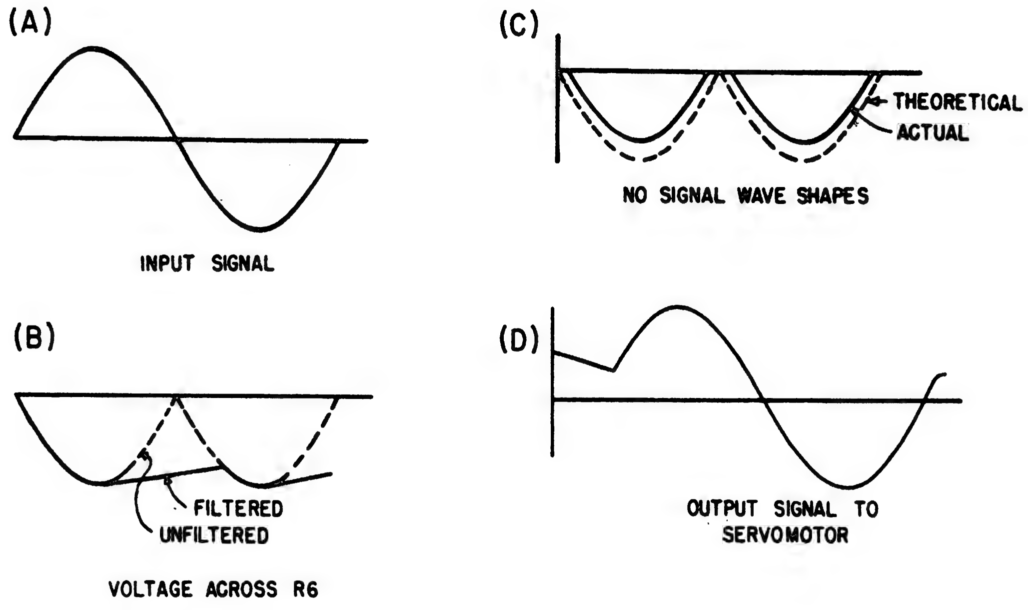

Figure 8-13.—Phase discriminator waveforms.

during the second half cycle. The output signal shown in figure 8-13 (D) has a large 400-hertz component in the second half cycle while the first half cycle has only a small 400-hertz component and a large 800-hertz component. The strong 400-hertz component in the second half cycle will produce a turning torque in the 2-phase servomotor. This torque causes the servo shaft to rotate in a direction which reduces the input signal to the servoamplifier. The signal is reduced to zero by positioning the synchro control transformer to electrical zero.

If the initial error signal had been of the opposite phase, the polarity of the signal at T1 would be exactly reversed (180° out of phase). As a result, the output signal from T4 would have a large 400-hertz component during the first half cycle rather than during the second half cycle, as in the case previously described. Hence the servomotor would rotate in the opposite direction, as is characteristic of 2-phase motors.

Amplifier Operation

The overall operation of the compass amplifier is described to present a general understanding of the circuit. A detailed description of each circuit follows.

The input to the compass amplifier is the rotor voltage of the compass detector synchro S2, as may be seen in figure 8-11. This signal is amplified in a 2-stage voltage amplifier (V10 and V11). Since the frequency of the output signal from the fluxvalve compass transmitter and hence the input signal to V10 is 800 hertz, it is necessary that the frequency of the voltage applied to the plates of V12 and V13 also be 800 hertz for proper discriminator action. The d-c output of the discriminator is amplified in a push-pull d-c amplifier (V14 and V15) and is further amplified in a push-pull magnetic amplifier. The output from the magnetic amplifier is a direct current that is proportional in magnitude to the 800-hertz a-c input signal, and the polarity depends on the phase of the input signal.

This output signal from the compass amplifier unit is fed to the slaving torque motor in the gyro unit. Referring to figure 8-8, it can be seen that the SYNC indicator is in series with one of the output leads from the compass amplifier. As mentioned previously, when the vertical white marker in the indicator is

approximately centered, it shows that the output signal from the compass amplifier is near null and that synchronization exists between the fluxvalve compass and gyro. Any error signals developed by S2 causes the gyro to start precessing in a direction that nulls the error signal at the slow rate of approximately 2° per minute.

The output voltage from the magnetic amplifiers T8 and T9 (fig. 8-11) is approximately constant regardless of the magnitude of the error signal. This is also true of the output from the servoamplifier. As in the servoamplifier, this characteristic is achieved in the compass amplifier by incorporating a large amount of degenerative feedback. This occurs because the cathodes of V11, V12, V13, V14, and V15 are not bypassed with capacitors.

Frequency Doubler Operation

Referring to figure 8-14, assume that the windings connected to the diodes (rectifier) do not exist. If this were the case, T6 and T7 would act simply like a transformer and produce two 400-hertz sinusoidal output voltages, E1 and E2, which would cause currents I1 and I2 to flow in the direction represented by the arrows. However, note that the sum of E1 and E2 would produce a zero output voltage since they are equal in magnitude and are opposing.

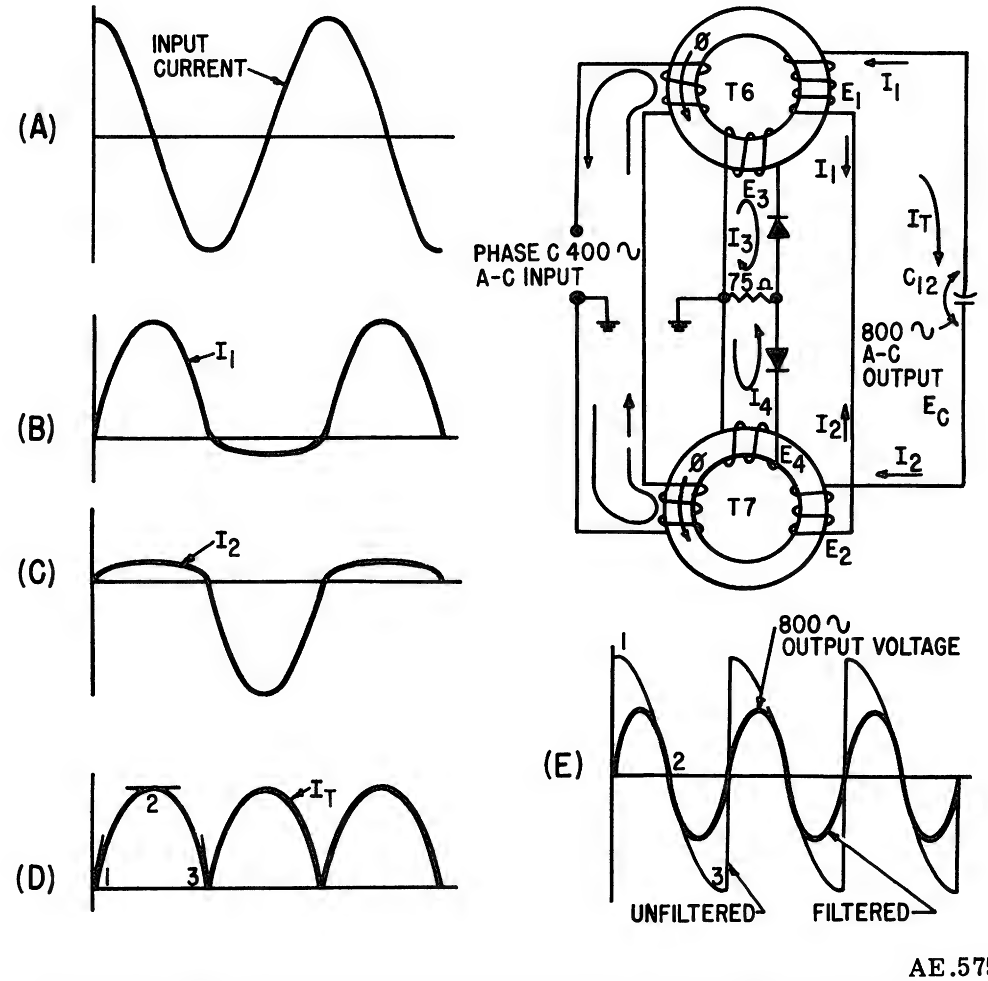

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Figure 8-14.—Compass amplifier frequency doubler and waveforms.

If the diode windings are considered to be in the circuit, the lower diode will conduct during the first half cycle and the upper diode during the second half cycle.

The impedance of these diode circuits is high when there is no conduction, and drops to a low value of approximately 75 ohms when conduction occurs. As in a conventional transformer, when the secondary impedance is low, the impedance reflected into the primary is also low. Again, referring to figure 8-14, it can be seen that when I4 flows, the impedance of T7's primary is low, thus causing most of the input voltage to appear across T6's primary. For this reason, I1 is large and I2 quite small during the first half cycle, as shown in figure 8-14 (B) and (C). Likewise, during the second half cycle, the other diode conducts which causes I2 to be large and I1 small. The sum of these two currents, I_T, which flows through C12 is shown in figure 8-14 (D).

The voltage across C12 is proportional to the rate of change of flux in T6 and T7. This change is approximately equal to the rate of change of the current.

Referring to the current waveshape in figure 8-14 (D), it may be seen that the slope at point 1 is maximum in a positive direction. Therefore, the voltage is maximum at point 1 as can be seen in figure 8-14 (E). At point 2 the slope is zero. At point 3 the slope is maximum in the negative direction. The voltages corresponding to points 1, 2, and 3 are shown by the heavy sine wave in figure 8-14 (E). The unfiltered voltage, which is the result of the 800-hertz output of E1 and E2, is shown by the light line in figure 8-14 (E). This is a theoretical voltage. After being filtered by C12, this voltage appears in the near half-sinusoidal form as shown by the heavy line in figure 8-14 (E).

Discriminator Operation

The plate voltage supplied to V12 and V13 are 800-hertz reference voltages which are exactly in phase, as may be seen in figure 8-15. The 800-hertz input signals to these tubes, on the other hand, are 180° out of phase, as shown. With no signal applied, V12 and V13 conduct equally when their plates swing positive, and develop equal voltages across R23 and R25. Thus, the grids of V14 and V15 have equal voltage on them, and will conduct equally.

Assume that an error signal fed into V10 is such that the output voltage developed across the secondary of T5 is as shown in figure 8-15. During the first half cycle, V12 conducts heavily, developing a large voltage across R23 since V12's grid and plate are both positive simultaneously. During the second half cycle, it does not conduct at all.

During the first half cycle, V13 barely conducts since its grid is negative while its plate is positive. Thus, the voltage developed across R25 is less than during no-signal conditions. During the second half cycle, neither V12 nor V13 conducts since their plates are negative.

The sum of the voltages across R23 and R25 is applied across R24 and R26 (fig. 8-15), where it is initially divided equally and filtered. Therefore, a negative voltage is applied to V14, cutting off its conduction. A positive voltage is applied to V15 which makes it conduct heavily. When this happens, the low value of cathode and tube resistance across R26 reduces the signal voltage across R26. This causes most of the signal voltage developed across R23 and R25 to appear across R24. This characteristic increases the amount of control action of the output circuit.

Had the input error signal been 180° out of phase, V15 would then be cut off and V14 would conduct heavily.

Magnetic Amplifier Operation

When studying the magnetic amplifier (fig. 8-16) refer to the symbols and waveforms in figure 8-17.

Load windings are generally labeled A1 to A2 and B1 to B2; while control or bias windings are labeled F1 to F2, F3 to F4, F5 to F6, etc. Assuming the electron flow is represented by I1, I2, and I3, fluxes are set up in the directions represented by the large arrows adjacent to the windings shown in the figure.

The operation of the magnetic amplifier may be understood better by referring to figure 8-16. The four cores comprising T8 and T9 are all magnetically independent, although controlled by common windings from V14, V15, and the bias circuit.

During no-signal conditions, V14 and V15 would conduct equally. Thus, control windings F3 to F4 and F6 to F5 would produce equal and opposite fluxes, which would cancel each other in T8 and T9. This is shown by the arrows in figure 8-16. Hence, their overall effect on these cores is negligible.

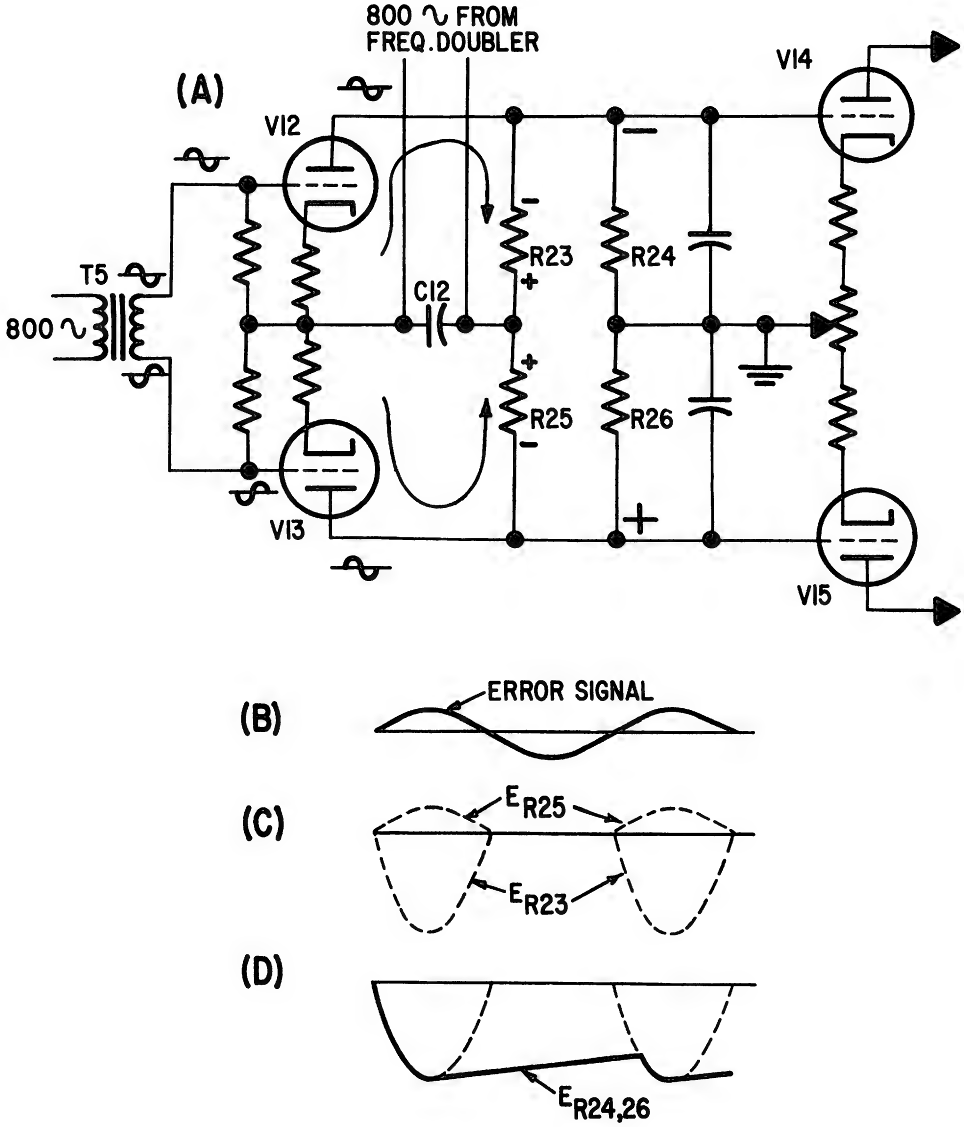

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Figure 8-15.—Discriminator section of compass amplifier unit.

The action of the load windings is as follows:

Assume that an a-c voltage with the polarity shown (fig. 8-17 (B)) exists on the secondary of phase C. Diodes DR2a and DR2b would conduct during the first half cycle and produce flux in the A1 to A2 load windings in the directions represented by the large arrows.

When T8 and T9 are not saturated, their impedances are high; thus, most of the voltage from phase C's secondary is dropped across the load coils in T8 and/or T9. There is very little voltage across R33 and R34. However, as soon as T8 and/or T9 saturate, the impedance of the coils drops to a very low value and most of the voltage appears across R33 or R34, respectively. In a sense, this characteristic is similar to thyratron action.

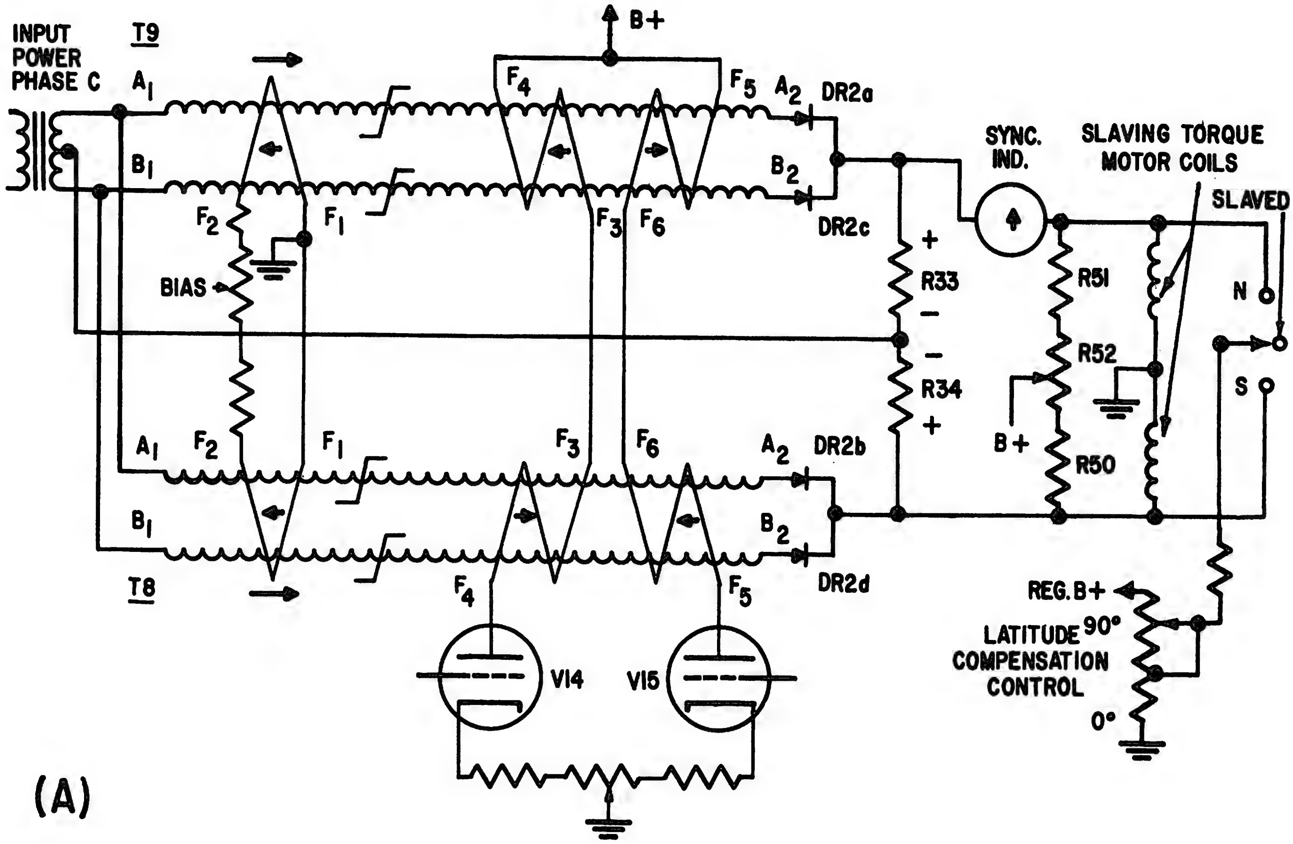

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Figure 8-16.—Magnetic amplifier in compass amplifier unit.

If no bias current is flowing, the current through DR2a causes T9 to saturate early in the first half cycle, and thus produce a voltage waveform across R33. (See fig. 8-17 (C).) Considering the effect of bias current, notice that the flux produced by the bias circuit opposes the flux described, thus tends to retard or delay the saturation of T9. Therefore, most of the input voltage appears across R33 later in the first half cycle. This is shown in figure 8-17 (D). DR2a and DR2c conduct alternately and thus produce a full-wave output across R33, as may be seen in figure 8-17 (D).

The voltage waveshape across R34 is exactly the same as across R33. However, the polarity of the voltage is exactly opposite, so that during no-signal conditions these voltages cancel each other. Assume that a signal causes V14 to conduct heavily and V15 only slightly. The flux produced in T9 by control winding F3 to F4 opposes the load winding flux represented by the large arrow and thus further retards the saturation of T9. (See fig. 8-17 (E).) However, the flux produced in T8 by current flow through V14 aids the flux produced by the current through DR2b and DR2d. Therefore, the time of saturation is advanced, and the resultant voltage across R34 is as shown in figure 8-17 (F).

The sum of the voltages across R33 and R34, shown in figure 8-17 (G), is a d-c voltage which is applied to the slaving torque motor coils. Had the input error signal been in the opposite direction and of the same magnitude, the output voltage waveshape would be the same as shown in figure 8-17 (G), but with the opposite polarity.

During no-signal conditions, very small equal and opposite currents flow through the slaving torque motor coils, due to the B voltage applied to the coils through R50, R51, and R52 (fig. 8-16). When an error signal exists and a d-c voltage is produced across R33 and R34, as already described, a current flows through both

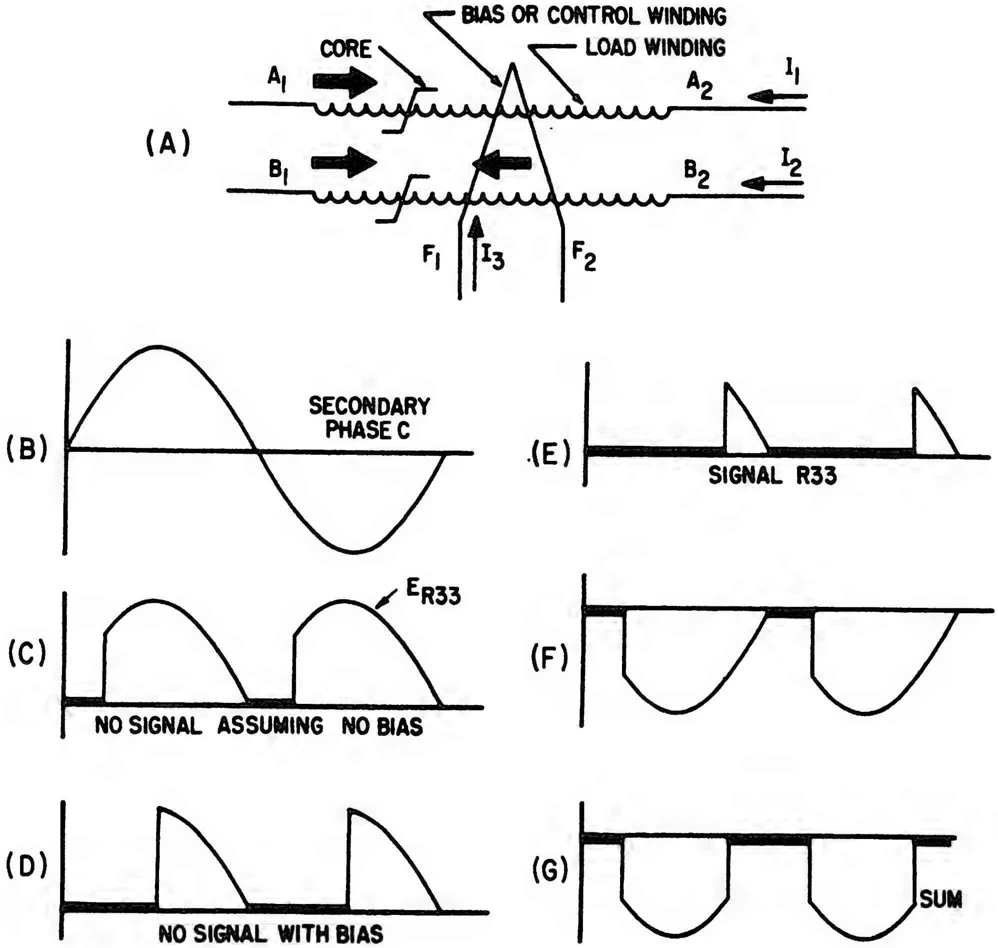

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Figure 8-17.—Magnetic amplifier waveforms.

torque motor coils from the magnetic amplifier. This current aids the B+ voltage in one coil and bucks the B+ voltage in the other. This causes a torque to be applied by the slaving torque motor that makes the gyro precess in azimuth in such a direction as to cancel the original error signal.

When the MA-1 is being utilized without compass slaving, a small latitude compensation voltage is fed to either the right or left torque motor coil. The coil to which it is fed depends upon whether the MA-1 is in the north or the south latitude. This is illustrated by the switch shown in the slaved position in figure 8-16.

Leveling Amplifier Operation

The leveling amplifier consists of one voltage amplifier stage (V16) and a four-tube power amplifier stage (V17, V18, V19, and V20). (See fig. 8-18.) Its function is to amplify signals from the leveling pickoff of the gyro to an amount suitable for operating the leveling torque motor.

Assume that the phase relationship of the leveling pickoff voltage applied to the grid of V16 is as shown in (A) of figure 8-18. The relation of this voltage to phase A voltage is shown at (B) and (C). V17 and V18 conduct

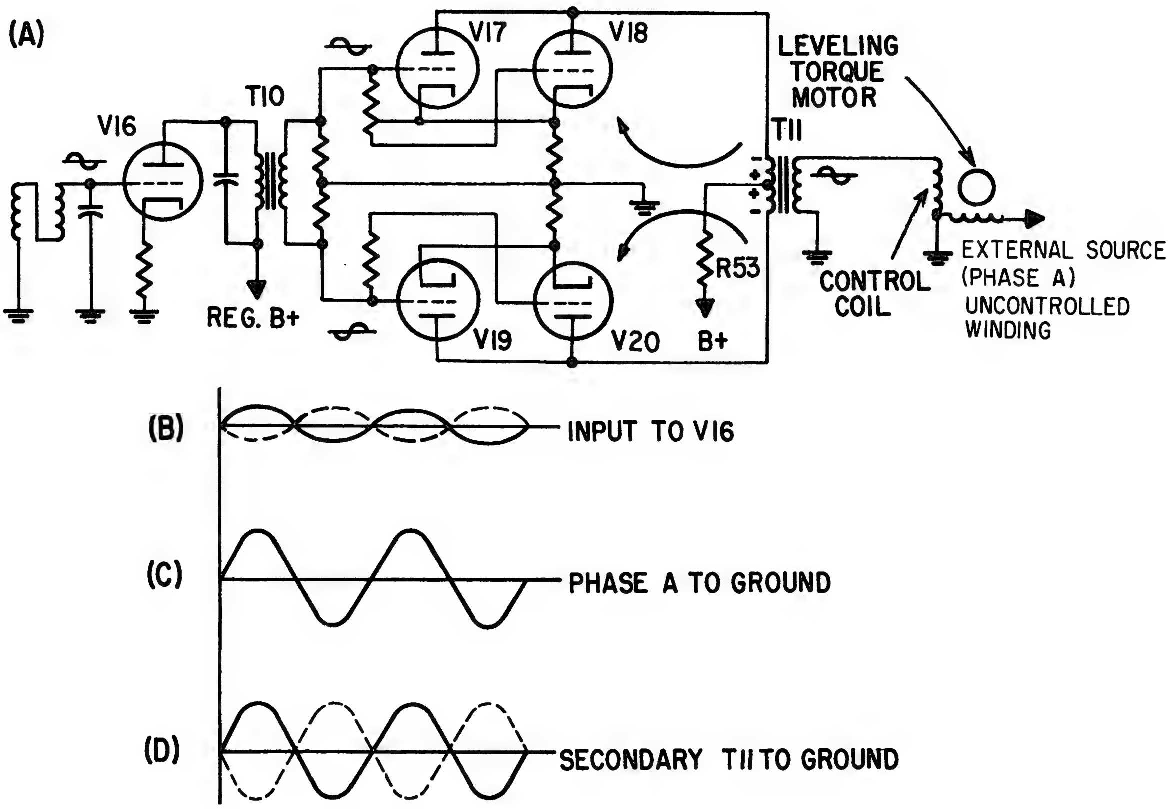

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Figure 8-18.—Leveling amplifier circuit.

heavily during the first half cycle, and V19 and V20 conduct heavily during the second half cycle. This is conventional push-pull amplifier action. With the signal as shown, the voltage output from T11 has the phase relationship shown by the solid line in figure 8-18 (D). When this voltage is applied to the leveling torque motor, it causes the gyro's axis to precess back to the horizontal position, and thus reduces the level pickoff voltage to zero.

Had the gyro's axis been displaced in the opposite direction, the input signal to V16 and output from T11 would be as represented by the dashed lines in figure 8-18 (B) and (D). The leveling motor would then have caused the gyro to precess in the opposite direction.

OPERATION SUMMARY

The manner in which the various elements of the system function is described in the following paragraphs. During this description refer to figure 8-11, which is an overall schematic of the system.

Compass Controlled Operation

The electrical output of the synchro transmitter S5 in the gyro unit corresponds to the position of the gyro spin axis. This output is fed to synchro differential S4 in the controller. The electrical output of the synchro differential corresponds to the angular position of the gyro spin axis plus the angular mechanical position of the synchro differential rotor. The output of the differential is fed to a synchro control transformer S1, which is coupled electrically to a servo shaft in the amplifier. The synchro control transformer rotor produces a signal that corresponds to the difference between the angular position of the servo shaft. This signal is amplified by the servoamplifier and is applied to the control phase of the servomotor M1. The servomotor rotates the control transformer

rotor (servo shaft) to null the output of the control transformer. The direction of the electrical field in the control transformer S1 is determined by the mechanical position of the synchro differential rotor plus the electrical signal from the synchro transmitter S5. When the rotor of the synchro control transformer S1 is perpendicular with the electrical field across the stator of S1, no signal is transmitted to V5 in the servoamplifier. The rotor of the synchro control transformer S1 follows any movement in the rotor of S4 or the electrical field of S5.

The compass detector synchro S2, which is mechanically coupled to the servo shaft, produces a signal that is a function of the difference between the magnetic compass heading and the angular position of the servo shaft. This signal is amplified in the compass amplifier and converted to a direct current that flows through the synchronization indicator to the slaving torque motor of the gyro and causes the gyro to precess slowly. Precession of the gyro causes the servo shaft to rotate in the direction that brings the output of the compass detector synchro S2 to a minimum. Since the gyro precesses slowly, only the average compass heading is obtained.

When the system is initially energized, there may be a large discrepancy between the compass heading and the angular position of the servo shaft. Due to the slow precession rate of the gyro, a long period of time would be required for the gyro position and magnetic heading to become synchronized. However, by rotating the shaft of the synchro differential S4 and observing the indications on the synchronization indicator, the servo shaft is quickly alined with the compass heading.

Free Gyro Operation

During free gyro operation, a latitude compensation voltage, which varies in magnitude with latitude, is applied to the gyro's slaving torque motor coils. The rate of precession at a given latitude is such that it exactly opposes the apparent drift of the gyro caused by the earth's rotation.

Before takeoff, the aircraft's heading is set on the output synchro (compass indicator) by rotating the synchro differential in the controller unit to the proper position. During the flight the gyro will then hold the rotor of the compass indicator in the same position in space. Therefore, assuming that grid navigational charts are used, the compass indicator always indicates the aircraft's heading.

MF-1 COMPASS SYSTEM

The MF-1 compass system features roll stabilization which reduces heading errors caused by gyro gimbal inclination when an aircraft is banked. Roll stabilization is accomplished by servoing the roll gimbal of the directional gyro in accordance with vertical reference information supplied by a separate vertical source.

In addition to the roll stabilization feature, the MF-1 system differs from other compass systems in that it can drive more repeaters and is adaptable to both 3-wire and 4-wire power sources. The clutched autopilot synchro transmitter is not influenced by magnetic information as it is in other types of compass systems. Since the clutched synchro transmitter is subject only to directional gyro information, latitude correction is applied to the directional gyro in both the slaved and free gyro modes to improve the accuracy of the output data.

The MF-1 compass reference system provides accurate directional information for navigation at all latitudes of the earth. The inertial element of this system, the roll stabilized directional gyro, provides accuracy in all regions of the earth. The magnetic element, the remote compass transmitter, provides a long-term reference with good accuracy in regions where the magnetic information is reliable. In the MF-1 roll stabilized directional gyro system, both of these references have been combined to provide accuracy and versatility. The compass system combines the inertial reference and the magnetic reference in one mode of operation and also provides each separately.

OPERATION

The MF-1 compass design incorporates a roll stabilized gimbal within the directional gyro. This stabilized gimbal eliminates errors usually caused by conventional directional gyro gimbaling arrangements. By stabilizing the roll gimbal of the instrument, the directional gyro is maintained in a horizontal position during aircraft maneuvers about the roll axis.

The roll stabilized gimbal, therefore, eliminates the gimbal error in the output data caused by the azimuth and axis being displaced when

the aircraft is in a roll attitude. It also eliminates the gimbal error when there is a shift in the position of the spin axis when the gyro hits the stop pins as the aircraft encounters a roll angle exceeding the gimbal stop position.

The roll gimbal provides 360° freedom about the roll axis. It is stabilized by a servomechanism which is operated by a synchro output signal from the vertical gyro. Thus, the roll gimbal maintains the spin axis of the directional gyro horizontally to the true vertical. The servomechanism consists of a control transformer that is back-to-back with the vertical gyro transmitting synchro, a transistorized servoamplifier, an electric servomotor, and a gear train. The synchro transmitter is mounted on the roll gimbal of the vertical gyro, and the control transformer is mounted on the stabilized roll gimbal in the directional gyro. The sensor develops a signal that is a function of bank angle.

The signal, after amplification, causes the servomotor to drive a gear train which is connected to the stabilizer roll gimbal to keep the directional gyro transmitter horizontal. The servomotor also incorporates a rate generator which is used for servo loop damping.

The roll gimbal is electrically alined to the horizontal plane of the fixed frame to within 1°. The roll gimbal is automatically locked in this position in case of loss of power to the roll stabilization circuit and when roll stabilization is turned off. An alinement light (push to test) is provided on the roll stabilization control panel. The lamp will light only when the test switch is pushed and the angle between the roll gimbal and the case is greater than 5°.

To correct for error due to the earth's rotation, a latitude corrector consisting of a direct current type of azimuth torquer is used to precess the azimuth gimbal.

As a leveling device, the directional gyro has an electrolytic switch and a split-phase torquer erection system. This system levels the gyro at a rate of 2° to 4° per minute. Provisions for electrically checking the performance of the leveling and roll stabilization channels are made on the side of the gyro base.

Two synchros are mounted on the azimuth axis of the gyro to transmit signals proportional to the position of the gyro. The azimuth transmitter operates the azimuth servochannel in the servoamplifier.

The functioning of the MF-1 compass system is shown schematically in figure 8-19. This is a simplified schematic and does not show all the components of the system. For more detailed schematics and diagrams, refer to the current NavAir Operation and Service Instruction Manual.

Directional Gyro Mode

During the directional gyro mode of operation, the heading reference for the system is the roll stabilized directional gyro. The directional gyro transmitting synchro is coupled back-to-back with the azimuth control transformer in the amplifier.

The rotor of the azimuth control transformer and the clutched synchro transmitter are mechanically coupled to the output of the azimuth servomotor generator gear train. The electrical output of the control transformer feeds into the azimuth servoamplifier in the amplifier unit. The azimuth servo and its associated gear train rotate the output shaft through the output differential, thus positioning the data synchro transmitters. The data shaft, the data transmitting synchros, and the clutched synchro transmitter move rapidly and accurately in response to the heading changes as measured by the directional gyro.

In the DG mode of operation, the correction shaft is servoed for the purpose of course setting. The correction shaft is mechanically coupled to the slew-slave motor through a two-speed gear train. When the slew control in the compass controller is turned, the slew gear train clutch is energized and an electrical signal is fed to the slew-slave motor. The correction shaft is rotated at a fast or slow speed, depending upon the slew knob position. The output shaft in turn is rotated and positions the heading indicators. During course setting, the clutched synchro transmitter does not have to be disengaged as the azimuth output shaft is essentially braked.

In the DG mode of operation, the directional gyro is precessed to compensate for the apparent drift due to the earth's rotation. The precession is controlled by the signal from the control panel latitude correction potentiometer which is fed to the azimuth torquer on the inner axis of the directional gyro. The direction of the precession is determined by the hemisphere switch, and the rate is controlled by the setting of the latitude correction dial. The synchronizing indicator monitors the latitude correction signal.

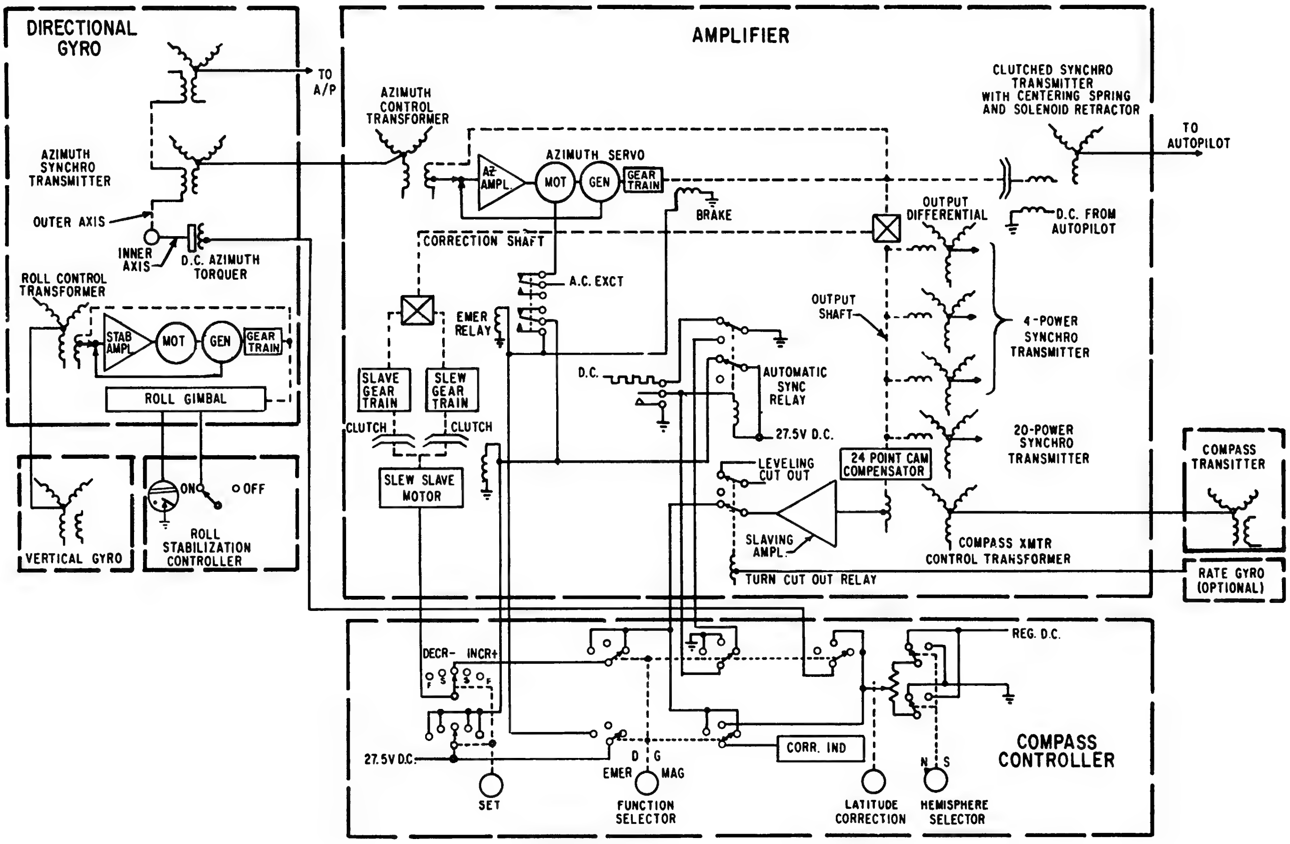

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Figure 8-19.—Simplified signal flow schematic of the MF-1 compass system.

Magnetic Mode

In the magnetic mode of operation, the roll stabilized directional gyro and the mechanism which servos the output shaft in proportion to directional gyro heading displacement still form the basic part of the system. The gyro is still precessed in accordance with the latitude signal to compensate for the apparent drift due to the earth's rotation. However, the correction shaft and, in turn, the output shaft are slaved in accordance with the remote compass transmitter heading information. The magnetic compass transmitter is coupled back-to-back with its followup control transformer in the servoamplifier unit. The followup control transformer rotor is positioned by the output data shaft through the cam compensator, and its output signal is fed to the slaving amplifier. The output signal of this amplifier goes through the turn cutout relay and the slew control and excites the slew-slave motor. This motor drives the correction shaft through the slave gear train at the slaving rate of 1° to 2° per minute until the compass control transformer is brought to null; i.e., the output data shaft is synchronized with magnetic or compass heading. Over this period, the compass information slowly corrects the output data shaft, and hence, furnishes long term stability.

In this mode of operation, it is necessary to initially synchronize the system; i.e., bring the output data shaft into agreement with magnetic heading. The operation is the same as for the DG mode except that the electrically operated magnetic clutch is energized through the automatic synchronization relays in order to shift the 2-speed gear train to the fast ratio (slew

gear train). The fast gear train enables slaving to be rapid and synchronization occurs quickly. This automatic synchronization occurs when the system is switched from the DG or EMER modes of operation to the MAG mode of operation, or when power is applied to the system, if the selector switch is in the MAG position. After the automatic synchronization cycle is completed, the slewing or synchronization motor can be actuated by the slew control in the controller to accomplish manual synchronization. During synchronizing, the clutched synchro transmitter does not have to be disengaged.

The synchronizing indicator which measures the compass amplifier output is part of the controller. This meter indicates the degree to which the output shaft is synchronized to magnetic heading since it is actually measuring the compass control transformer output. When synchronization is achieved, the meter is centered. However, during flight when in the slaved mode, the meter movement will normally oscillate slightly about its neutral position.

Emergency Mode

In the emergency mode of operation, the remote compass transmitter is the heading reference for the system. This mode can be utilized when the roll stabilized directional gyro or the azimuth servo loop is malfunctioning. The operation is similar to the correction loop of automatic synchronization. However, the excitation to the azimuth servomotor is removed, and its shaft coupled to the output differential is braked. Also, the slew gear train is constantly engaged. Thus the output shaft with the data transmitters responds to the magnetic compass at the synchronization rate.

SYSTEM OPERATIONAL CHECKS

An operational check of the compass system should be included in the preflight check of the aircraft. This assures that the compass system is operating properly and is ready for the flight. When troubleshooting the system, an operational check of the compass system is necessary before it can be determined which component or part of the system is at fault.

The Maintenance Instructions Manual for the aircraft or the Service Instruction Manual for the compass system gives the step-by-step procedures for the operational check.

Some of the daily inspection procedures of the roll stabilized gyro compass system are listed below:

1. Check for operation of the gyro motor by listening or by placing the fingers on the case of the directional gyro.
2. Observe the compass indicator while rotating the roll stabilized directional gyro horizontally as far as the shock mounts permit, first clockwise, then counterclockwise. The pointer of the compass indicator should follow in the same direction, indicating proper operation of the heading synchro in the roll stabilized directional gyro and the azimuth servo loop in the compass servoamplifier.
3. With the roll stabilizer switch in the ON position the roll stabilized directional gyro should be level. Tilt the vertical gyro or rotate the vertical gyro simulator. The third gimbal, as observed through the opening on the roll stabilized directional gyro, should move in conjunction with the vertical gyro or simulator, compensating for their change of position.
4. Set the compass controller to the DG mode of operation. Observe the azimuth indicator dial. The indicator dial should stop moving and oscillating within 30 seconds after power has been applied.
5. Turn the SET switch on the compass servoamplifier to INCR or DECR and hold until the heading indicator moves approximately 90° from the synchronized heading. Turn the function selector switch on the control panel from MAG to DG and back to MAG position. The compass indicator pointer should synchronize automatically to the approximate aircraft magnetic heading within 15 seconds. The correspondence indicator pointer on the compass controller should be alined (within 4 minutes) with the center index line.
6. Turn and hold the SET switch to the last index toward the INCR position. The compass indicator pointer should rotate smoothly and rapidly in a clockwise direction. Repeat the test for counterclockwise rotation by turning and holding the SET switch to the last position toward DECR.

Refer to the applicable Operation and Service Instruction Manual for the correct voltage checkpoints and voltage testing procedures.

CAUTION: If it is necessary to remove the roll stabilized directional gyro from its mounting location while the gyro is spinning but not energized, move it with care as excessive tilting of the roll stabilized directional gyro may

cause the gyro to tumble and cause damage to the instrument.

TROUBLESHOOTING

Sometimes a complete component of a system is unnecessarily replaced. After troubleshooting, it may be determined that a faulty tube, fuse, or an inadequate power supply was the trouble. Changing a complete unit to correct such a simple defect is very costly and time consuming. However, it is true that in some cases a new unit would be necessary to correct the trouble.

The maintenance and testing of gyro stabilized compass systems usually consist of voltage checks and operational tests of the various components. The correct voltages and the voltage checkpoints are given in the Maintenance Instructions Manual for the particular aircraft and also in the Operation and Service Instruction Manual for the compass.

The roll stabilized gyro compass system should be inspected daily for correct operation. Check the gyro motor of the directional gyro by listening or by placing your fingers on the case of the roll stabilized directional gyro. Rotate the roll stabilized directional gyro horizontally as far as the shock mounts permit, first clockwise, then counterclockwise; the pointer of the compass indicator should follow in the same direction. This movement indicates proper operation of the heading synchro in the directional gyro and the azimuth servo loop in the compass servoamplifier.

The servoamplifier should be checked by placing the SET switch on the controller to the INCR or DECR position and holding the switch in that position until the heading indicator moves approximately 90° from the synchronized heading. With the function switch in the MAG position, the switch is placed in the DG position, then back to the MAG position; the compass indicator should synchronize automatically to the approximate aircraft magnetic heading within 15 seconds. The correspondence indicator pointer on the compass controller should aline with the center index line within 4 minutes.

The daily inspection procedures for the compass system may be found in the Operation Instruction Manual or Maintenance Instructions Manual.

A troubleshooting chart is useful and can save hours of work if it is well planned. Such a chart should contain a listing of the major components of the system, the major parts of each component, and a brief description of how the system acts when a particular part fails. For efficient troubleshooting, the principles of operation of the compass system and the symptoms for failures of any of its major components should be committed to memory.

CHAPTER 9
ATTITUDE REFERENCE BOMBING COMPUTER SYSTEM

An attitude reference bombing computer system is essentially two systems combined into one: (1) an all-attitude indicating or display system, and (2) a low altitude bombing system. The all-attitude indicating portion of the system gives the pilot a visual display of heading, pitch, roll, and rate-of-turn. The low altitude bombing portion of the system enables the pilot to perform accurate low altitude bomb delivery maneuvers which consist of two primary methods of bomb delivery: (1) a low angle bomb release (loft bombing), and (2) a high angle bomb release (over-the-shoulder bombing).

The attitude reference bombing computer system that is discussed in this chapter is the AN/AJB-7, which is installed in the F4-J aircraft. The AN/AJB-7 is similar to its predecessors, the AN/AJB-3A and -3, which are installed in the F4-B and the A4, respectively. The all-attitude indicating system of the AN/AJB-7 is similar to many of the attitude flight reference systems found in the later types and models of Navy and Air Force aircraft. Essentially, the difference between the AN/AJB-7, -3A, and -3 systems and other similar attitude flight reference systems is that the AJB systems have the additional capability of performing low altitude bomb delivery.

ATTITUDE REFERENCE BOMBING COMPUTER SET AN/AJB-7

The Attitude Reference Bombing Computer Set AN/AJB-7 is an all-attitude reference system with a special purpose bomb director. The all-attitude reference system provides the pilot with an accurate display of aircraft attitude through 360° in pitch, roll, and azimuth. The special purpose bomb director provides the commands for executing the bombing maneuver and for automatic bomb release.

The computer set, in addition to its primary functions, provides attitude information to other aircraft associated systems such as the AN/ASA-32H autopilot and the AN/AWG-10 missile control system.

ALL-ATTITUDE DISPLAY SYSTEM

The AN/AJB-7 uses a three-axis servo-controlled readout sphere to present a continuous all-attitude display to the pilot. The attitude indicator, which houses the sphere, is mounted on the instrument panel, directly in front of the pilot. Any given attitude of the aircraft is presented to the pilot via the sphere, which is capable of rotating 360° about the roll, pitch, and azimuth axes. Any complex attitude assumed by the aircraft is thus graphically presented to the pilot. One reference point for this all-attitude determination is obtained from the displacement gyroscope assembly. The gyroscope mount is properly oriented and precisely alined to the longitudinal and lateral axes of the aircraft. Figure 9-1 is an illustration of the attitude indicator.

Azimuth Display

Azimuth or heading information is displayed by vertical marks in 5° increments horizontally about the center of the attitude indicator sphere. The azimuth information may be supplied by one of three references selected by the mode switch on the compass controller: (1) unstabilized magnetic heading from the flux valve, (2) stabilized magnetic heading, or (3) by using the directional gyro only as a heading reference.

Attitude Display

Aircraft attitude is displayed on the sphere of the attitude indicator in 360° of pitch and roll. Also, aircraft rate-of-turn is displayed by a rate-of-turn pointer located on the attitude indicator just below the attitude sphere.

PITCH AND ROLL.—Pitch and roll reference information is supplied by the vertical gyro, located in the displacement gyro assembly, when STBY is selected on the primary-standby switch on the compass controller. When the compass controller primary-standby switch is in the PRIM position, pitch and roll reference information is supplied by the Geocentric

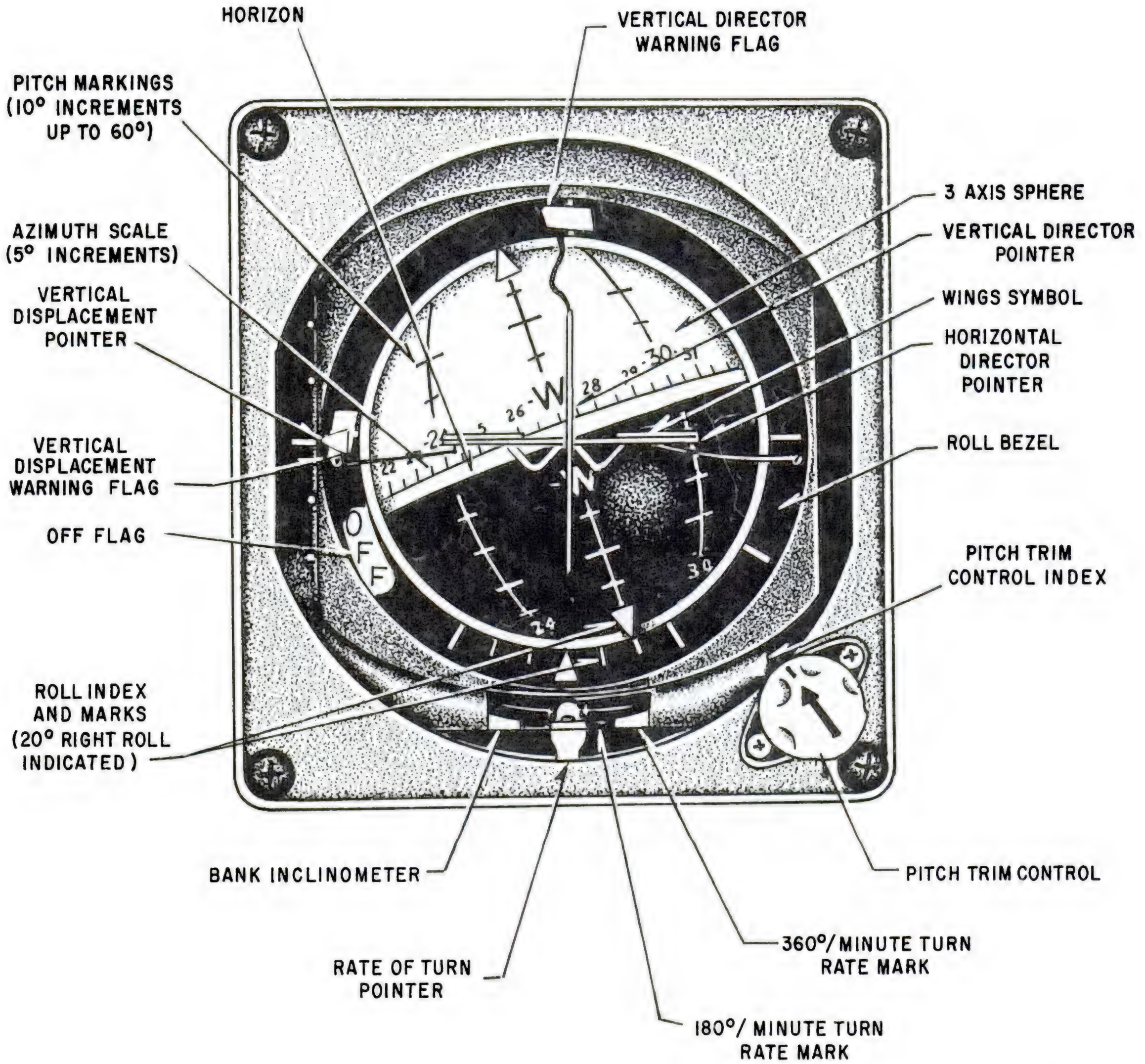

Figure 9-1.--Attitude indicator flags and pointers.

Vertical Flight Reference Set AN/ASN-70, which is discussed in the latter part of this chapter.

NOTE: The F-4J model aircraft also contains a pilot's standby attitude indicator and a rear cockpit remote attitude indicator. Both of these indicators receive pitch and roll attitude reference information from the AN/AJB-7 displacement gyro assembly regardless of the position selected by the compass controller PRIM-STBY switch.

RATE-OF-TURN.--The rate-of-turn pointer on the attitude indicator receives rate-of-turn reference information from the rate gyro transmitter. The rate gyro transmitter senses the direction and rate of aircraft turns about the aircraft yaw axis and transmits this rate-of-turn information to the indicator in the form of a d-c voltage proportional to the rate of aircraft turn.

LOW ALTITUDE BOMBING FUNCTIONS

There are four bombing functions or modes available for a bombing run: (1) loft, (2) timed

over-the-shoulder, (3) instantaneous over-the-shoulder, and (4) direct. The mode is selected by positioning the bomb control switch on the aircraft main instrument panel. Once initiated, any bombing run (except direct) may be canceled by releasing the bomb button, yawing the aircraft more than 30°, or placing the bomb control switch to the OFF position.

Loft

A loft bombing run is a low altitude, low angle release bombing run. A typical loft bombing run is illustrated in figure 9-2. The identification point (IP), PULLUP time interval (TI), and LOW ANGLE release setting are set in before the run is initiated. The pilot depresses the pickle button over the identification point which centers the horizontal and vertical flight director pointers on the attitude indicator. One second before the end of the preset PULLUP time interval, a short warning tone burst is produced in the headsets. At the end of the timed interval, the LABS lamp lights and a continuous tone is produced in the headsets. The pilot immediately begins pullup and flies the aircraft so that the horizontal and vertical pointers remain centered. The horizontal and vertical pointers determine the accuracy of the bomb drop; the closer to the center position both are kept, the more accurate the drop will be.

To maintain the horizontal director pointer on center requires that the pilot linearly increase the pitch attitude until the aircraft pulls 4 g's after 2 seconds. The vertical director pointer is sensitive to bank and yaw deviations and will be displaced from center an amount proportional to the deviation. The bomb is automatically released at the preset release angle. Upon release of the bomb the LABS lamp goes out, the steady tone ceases, and the vertical director pointer is deflected out of view. The pilot continues to hold the bomb button depressed and continues the Immelmann maneuver, keeping the horizontal flight director pointer centered until inverted flight is reached. Upon reaching inverted flight, the pilot releases the pickle button and rolls the aircraft out, completing the maneuver.

Timed Over-the-Shoulder

The timed over-the-shoulder bombing run is a low-altitude, high angle release bombing run. A typical timed over-the-shoulder bomb run is illustrated in figure 9-3. It is essentially the same as a loft run except that bomb release is set in with the flight director bombing computer HIGH ANGLE control and the release occurs at an aircraft pitch angle greater than 90°. The bomb crosses the aircraft path after the aircraft has made its escape.

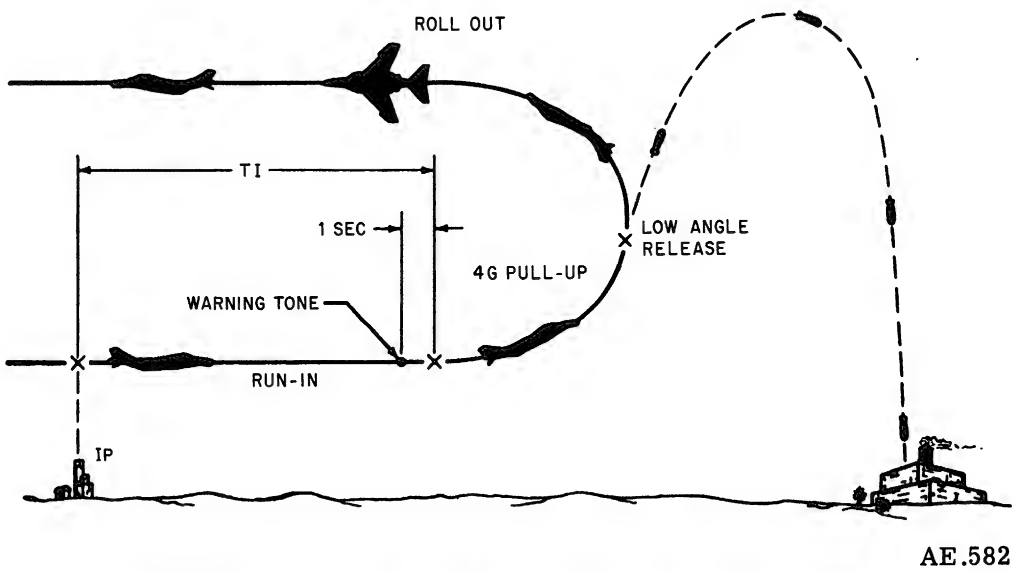

Figure 9-2.—Loft bombing run using Immelmann maneuver.

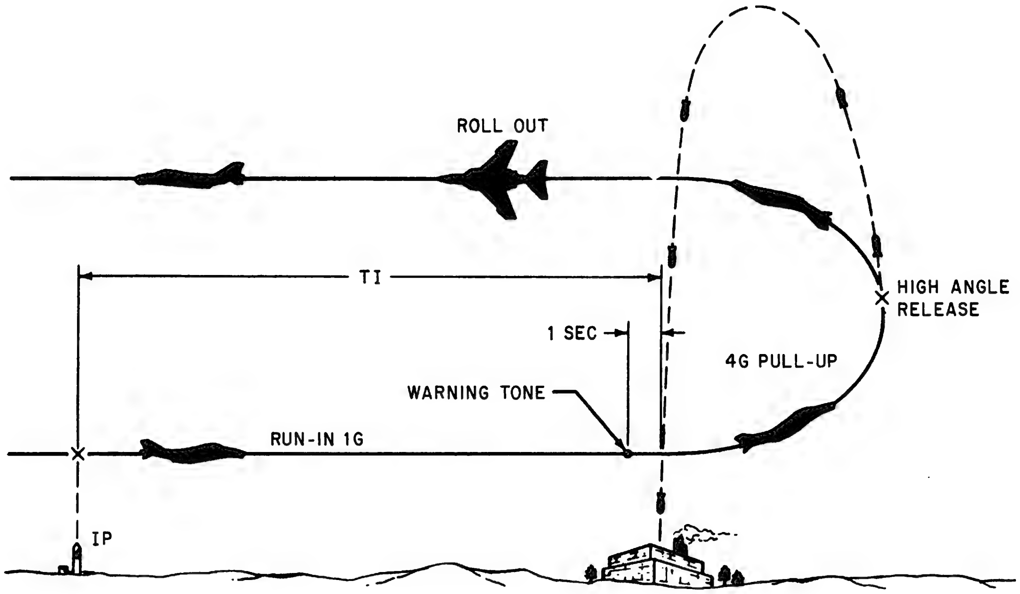

Figure 9-3.—Timed over-the-shoulder bombing run.

Instantaneous Over-the-Shoulder

The instantaneous over-the-shoulder method of bomb delivery does not require an identification point or a timed interval. The bomb button is depressed directly over the target and pullup is begun immediately. Bomb release, as in timed over-the-shoulder, is obtained at an angle greater than 90°, and the bomb follows a similar trajectory.

Direct

The direct method of bomb delivery is initiated by the pilot by selecting DIRECT on the bomb control panel. The bomb is released at the instant the pilot depresses the pickle (bomb) button.

DESCRIPTION OF COMPONENTS

Aircraft Accelerometer

The aircraft accelerometer provides an output voltage that is proportional to a linearly applied acceleration along its sensitive axis. This axis is normal (perpendicular) to the longitudinal axis of the aircraft. The aircraft accelerometer supplies g information to the flight director bombing computer; it is functionally part of the BOMBING GROUP.

Amplifier-Power Supply

The amplifier-power supply provides the necessary servoamplifiers and power requirements for proper operation of the gyroscope. The amplifier-power supply contains time-delay relays that control the application of spin and erection potentials to the gyroscope. This unit is functionally a part of the ATTITUDE REFERENCE GROUP.

Bomb Release Angle Computer

The bomb release angle computer provides bomb release and relay switching at preselected pitch angles. In addition, this unit resolves displacement gyroscope assembly output signals into aircraft roll and yaw signals. The servo loop contained in the bomb release angle computer amplifies and follows the pitch information obtained from the displacement gyroscope assembly. The resulting gear-train rotation positions the rotors of a control transformer, a control transmitter, and a resolver. The gear-train actuates a ±20° switch and a low angle and a high angle release switch.

High and low angle insertion control knobs, with their associated digital readout counters, make up the front-panel controls of the bomb release angle computer. This unit is functionally considered part of the BOMBING GROUP.

Attitude Indicator

The attitude indicator contains an all-attitude indicating sphere and flags and pointers whose specialized indicating functions are shown in figure 9-1. An amplifier-power supply assembly, attached to the rear of the attitude indicator, is a "piggyback" unit which contains a power supply and the pitch, roll, and azimuth servoamplifiers.

The sphere is assembled from two halves—the upper portion, which is white in color, represents the sky for climbing; and the bottom half is black for diving. A climb attitude is indicated by rolling the sphere toward the viewer or downward, which causes the white-black demarcation line (artificial horizon) to move downward. The degree of pitch is indicated in 10° increments. The attitude indicator is functionally a part of the DISPLAY GROUP.

Compass Adapter-Compensator

The compass adapter-compensator is required to process heading information from both the compass transmitter and the displacement gyroscope assembly. The compass adapter-compensator azimuth modes are compass, directional gyro, and slaved. Open printed circuit boards, interconnected by flexible printed wiring, are used for the servoamplifiers, demodulators, power supply, and synchro assemblies. The compass adapter-compensator also contains 24 compensating potentiometers for flux valve deviation compensation and a BIAS DEGREE/HOUR adjustment for compensating the average precession rate of the directional gyro. The compass adapter-compensator is functionally a part of the HEADING REFERENCE GROUP.

Compass System Controller

The compass system controller is used primarily to control the azimuth system. The various positions of the mode switch on the controller activate relays in the compass adapter-compensator, thus selecting the operating azimuth mode—compass, directional gyro, or slaved. Selection of primary (PRIM) and standby (STBY) attitude information is also provided by the compass system controller.

A spring-loaded, self-centering, push-to-turn type of set heading (SET HDG) control is provided to manually initiate a movement in the azimuth gear train. The PRIM-STBY switch selects either the AN/ASN-70 or the displacement gyro as a source of attitude information. The PRIM position provides AN/ASN-70 roll and pitch attitude information to the attitude indicator and the AN/AWG-10 radar system. A latitude (LAT) compensation control and an associated N-S hemisphere switch are provided on the front of the compass controller. This unit is a part of the HEADING REFERENCE GROUP.

Compass Transmitter

The compass transmitter, which is a flux valve or direction-sensing device, accurately detects its alinement relative to the horizontal component of the earth's magnetic field.

The pendulous sensing mass of the flux valve has a minimum of 27° of freedom or swing in all directions. The flux valve limitations or disadvantages include inaccuracies that result from excessive turns or abrupt attitude changes. Inaccuracies also result from distorted magnetic force fields found above 70° latitude or near large iron deposits. The flux valve, which is most useful when employed in conjunction with the displacement gyroscope assembly (slaved mode), also serves as an emergency source of heading information in the compass mode. The compass transmitter is a part of the HEADING REFERENCE GROUP.

Displacement Gyroscope Assembly

The displacement gyroscope assembly consists of two gyros—the vertical gyro and the directional gyro. The gyros are mounted in multiple gimbals supported by a common outer roll gimbal. This arrangement prevents "gimbal-locking" the vertical gyro. The displacement gyro is a functional part of the ATTITUDE REFERENCE GROUP.

Flight Director Bombing Computer

The flight director bombing computer provides a d-c signal, proportional to roll and yaw, for steering information during a bombing run; a d-c signal proportional to the g error; a 1200-Hz warning and pullup tone; and a heading synchronizing signal for yaw input to the bomb release angle computer. The flight director bombing computer is a part of the BOMBING GROUP.

Interval Timer

The interval timer is a timing device which is manually adjustable from 0 to 30 seconds, in

increments of 0.1 second. The required time setting for the bombing run is determined by the predicted flying time from the identification point to the pullup point. The timer clutch is engaged when the store release button is pushed, which commences timer rundown. This unit is a part of the BOMBING GROUP.

Rate Gyroscope Transmitter

The rate gyroscope transmitter provides a d-c signal that is proportional to the rate of displacement about the vertical axis of the aircraft. This output signal is applied to the rate-of-turn pointer on the attitude indicator. The rate gyroscope transmitter—which should not be confused with the switching rate gyroscope—detects and provides an immediate output when the aircraft yaws; it is an indicating device, whereas the switching rate gyroscope is as the name implies, a switching device. The rate gyroscope transmitter is considered a part of the DISPLAY GROUP.

Remote Attitude Indicator

The remote attitude indicator presents a visual display of aircraft pitch and roll. It contains a roll control transformer, a roll servoamplifier with its associated trim potentiometer (on the rear of the unit), and a motor-generator combination for driving the sphere about the roll axis. It also contains a pitch control transformer, a pitch servoamplifier and associated trim potentiometer (on the front of the unit), and a motor-generator combination for driving the sphere about its pitch axis. An OFF or failed condition is indicated by a flag.

The remote attitude indicator does not have 360° of freedom in pitch; however, by utilizing an illusion at a pitch angle approximating 90°, pitch angles greater than 90° can be visualized. After rotating approximately 90° in pitch, the sphere is rotated 180° in roll. At this point the pitch phase and the rotation of the pitch drive are reversed. The result, as far as the viewer is concerned, is as if the sphere moved passed 90° in pitch and continued toward 180°.

The remote attitude indicator is functionally a part of the ATTITUDE REFERENCE GROUP.

Standby Attitude Indicator

The standby attitude indicator presents a visual display of aircraft roll and pitch attitude through 360°. This 2-inch attitude indicator, located at the lower left side of the main attitude indicator, receives the same attitude reference information as the remote attitude indicator located in the rear cockpit. The standby and remote indicators receive ONLY AN/AJB-7 displacement gyroscope roll and pitch attitude information. The standby attitude indicator is functionally a part of the DISPLAY GROUP.

Switching Rate Gyroscope

The switching rate gyroscope interrupts gyro erection and slaving circuits when the aircraft rate-of-turn is equal to or greater than 15° per minute. This switching action (1) reduces vertical gyro errors caused by turn-acceleration forces acting upon the gravity-sensitive erection switches, and (2) minimizes azimuth slaving errors which occur when the pendulously suspended magnetic detector (flux valve) swings too far from vertical. The switching rate gyroscope is considered a part of the ATTITUDE REFERENCE GROUP.

MODES OF OPERATION

In the following discussion on the modes of operation of the AN/AJB-7, refer to figures 9-4 and 9-5 which show the forward and aft cockpit controls and indicators in the F-4J aircraft.

Note that the horizontal situation indicator and the bearing distance heading indicator are shown in figures 9-4 and 9-5, respectively. They are not part of the AN/AJB-7; they are part of the TACAN. However, their heading information is supplied by the AN/AJB-7; therefore, as far as the AE is concerned, they serve as compass repeaters.

Pitch and Roll Attitude Mode

There are two sources of pitch and roll attitude reference information supplied to the attitude indicator (forward cockpit): (1) the vertical flight reference set when primary mode is selected, and (2) the displacement gyroscope assembly when standby mode is selected. The PRIM-STBY mode switch is a two-position rotary switch located on the compass system controller.

The standby and remote attitude indicators receive their attitude reference information from the displacement gyro regardless of the position of the PRIM-STBY mode switch.

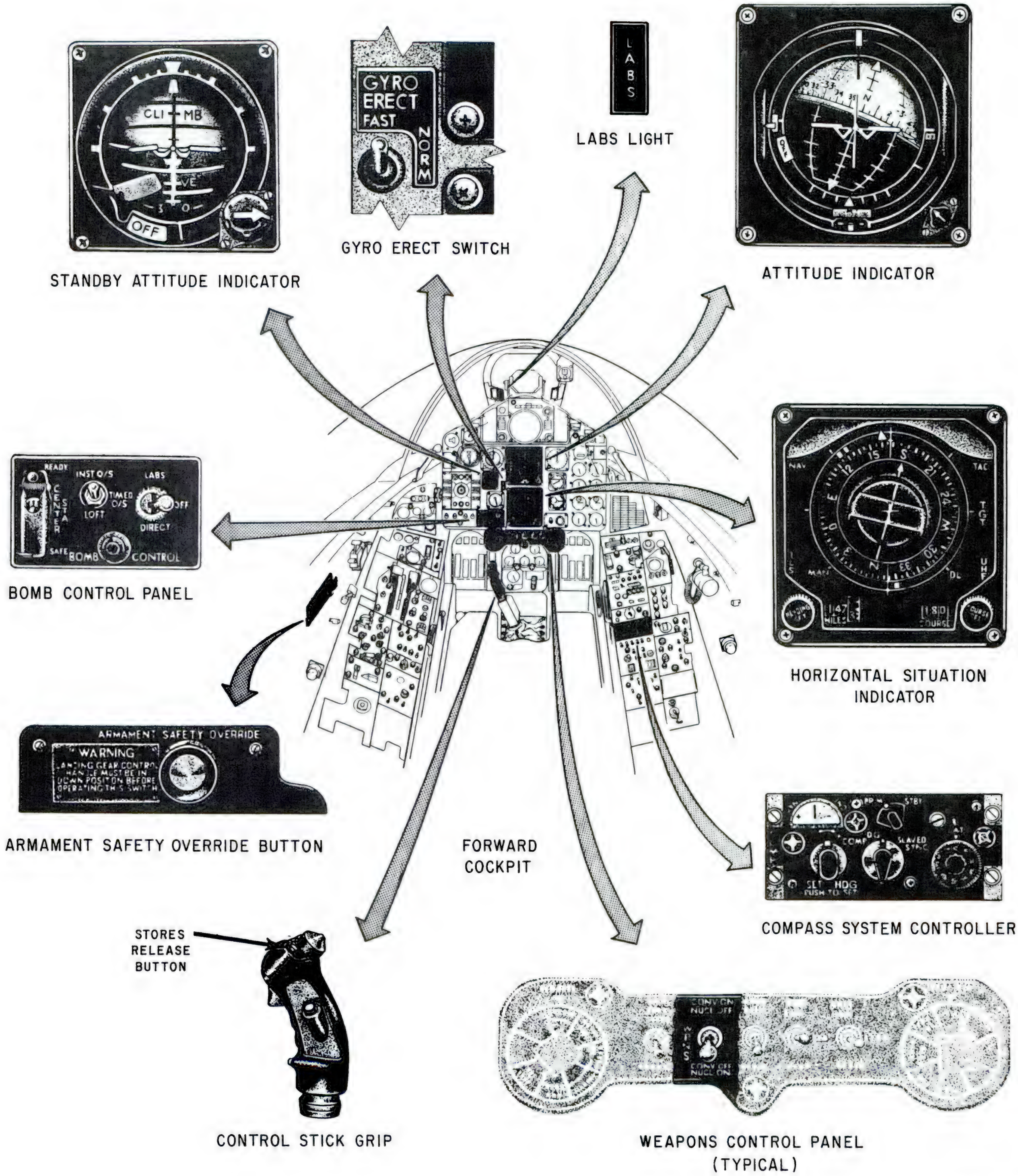

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Figure 9-4.—Controls and indicators, forward cockpit.

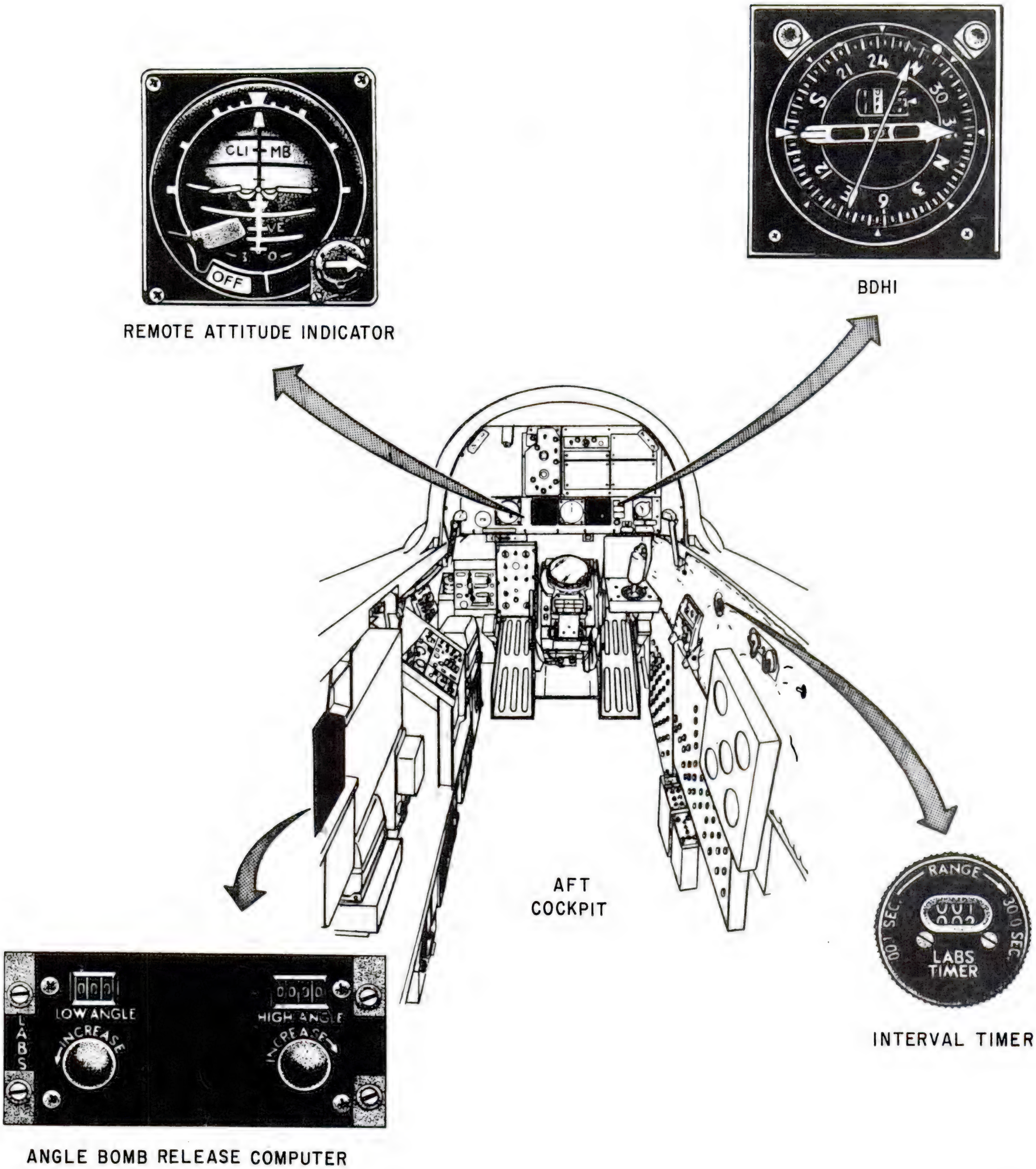

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Figure 9-5.—Controls and indicators, aft cockpit.

It should be noted that whenever there is a primary-standby mode transfer, the attitude indicator may or may not undergo a 180° change in pitch, roll, and azimuth. This is normal operation. In either case the sphere continues to display the correct attitude.

Some models of the F-4 aircraft employ a GYRO ERECT Switch (fig. 9-4), which is a

two-position switch—one position for normal erection voltages to the displacement gyroscope and the other position for fast erect voltages. In normal erection the displacement gyroscope gimbals are returned to level at a rate of 1° to 2° per minute; with the gyro erect switch in FAST, the displacement gyroscope gimbals are returned to level at a rate of 15° per minute. The purpose of FAST ERECT is to quickly erect the displacement gyroscope gimbals to the level position should they become unlevel during severe aircraft maneuvers. The FAST ERECT position is a momentary on switch position, and it should not be held in that position longer than 60 seconds. Failure to heed to this caution may damage the displacement gyroscope leveling torquers.

Azimuth Modes

The azimuth system may operate in any of three modes—compass, directional gyro, or slaved. The mode is selected with the mode switch on the compass system controller. The mode switch also has a spring-loaded SYNC position to provide manual fast synchronization in the slaved mode. The following paragraphs provide a brief description of the three azimuth modes and their operating instructions.

COMPASS MODE.—The compass mode utilizes magnetic heading information from the compass transmitter (flux valve) only. This mode is an emergency mode and is used when the directional gyro (in the displacement gyroscope assembly) malfunctions. When compass mode is selected, the interlock with the AFCS opens automatically and prevents application of erratic magnetic heading signals to the flight control group.

Compass mode is selected as follows: (1) Turn the mode switch on the compass system controller to the COMP position, and (2) place the PRIM-STBY switch to the PRIM position. Note that if PRIM is not selected, the attitude indicator will continue to display displacement gyroscope information.

DIRECTIONAL GYRO MODE.—The directional gyro mode utilizes change of heading (yaw) information from the directional gyro in the displacement gyroscope assembly. When the directional gyro mode is initially selected, aircraft heading must be manually set into the azimuth system with the SET HDG control on the compass system controller. The directional gyro mode is used in areas where the earth's magnetic flux lines are distorted or when the flux valve malfunctions.

To select directional gyro mode, (1) place the mode switch to DG; (2) press and turn the SET HDG control until the attitude indicator sphere indicates actual aircraft heading; and (3) insure that the N-S switch is set to local hemisphere, turn the LAT control to local latitude, and readjust it for each 5° change in latitude.

NOTE: Failure to set the N-S switch to local hemisphere adds to the heading error produced by apparent precession. If the N-S switch cannot be set to local hemisphere, turn the LAT control to 0.

SLAVED MODE.—The slaved mode utilizes magnetic heading from the flux valve and change of heading (yaw) from the directional gyro. The flux valve signal serves as the reference and the gyro yaw signal provides stabilization and fast followup. Should the change of heading signals from the two sources differ, the flux valve signal determines the final magnetic heading output for the system. Because system accuracy depends upon the condition of the earth's magnetic field, the slaved mode should not be used in latitudes greater than 70°, in areas where the magnetic field is distorted, or when the flux valve malfunctions.

To select slaved mode proceed as follows:

1. Turn the mode switch on the compass system controller to the SLAVED position.
2. Allow 10 seconds for automatic fast synchronization, and check the SYNC IND meter for center scale indication. There will be a slight deviation of the needle from center scale indication. This slight deviation of the needle from center position is corrected by the normal sync rate.
3. Momentarily place the mode switch to the SYNC position if the SYNC IND needle is off center after aircraft turns and maneuvers.

Bombing Modes

There are four bombing modes—loft, instantaneous over-the-shoulder, timed over-the-shoulder, and direct. The mode is selected by placing the LABS-OFF-DIRECT and the INST O/S-LOFT switches on the main instrument panel to the desired positions.

Before takeoff, the following information must be known: target information and bombing mode to be used, run-in altitude, speed and heading, time interval from the identification point to the pullup point, and the release angle.

NOTE: The bomb release angle must be adjusted for any gyro pitch error that may exist. The gyro error pitch correction is obtained from the Pitch Synchro Output Correction Chart on the displacement gyroscope assembly case. To make the correction, add algebraically the gyro error pitch correction to the required bomb release angle.

LOFT MODE.—The loft mode is a timed low angle (less than 90°) release mode requiring a previously determined identification point, time interval, and bomb release angle.

To execute the bombing run proceed as follows:

1. Set the prescribed time interval on the interval timer.
2. Set the LOW ANGLE control on the angle bomb release computer to the required release angle. The HIGH ANGLE control may be set at any angle.
3. Before reaching the identification point, place the LABS-OFF-DIRECT switch to LABS and the INST O/S-TIMED O/S-LOFT switch to LOFT.
4. Maintain predetermined altitude, heading, speed and wings-level attitude while approaching the identification point.
5. Press and hold the stores release button immediately over the identification point.

Once the stores release button is pressed, the following actions occur to which the pilot must respond: The attitude indicator horizontal and vertical pointers move to center; 1 second before pullup, a short warning tone is heard in the headsets and at the end of the timed interval the LABS lamp illuminates and a continuous tone is heard. At this point the pilot starts his pullup and flies the aircraft so that the horizontal and vertical pointers are maintained at center. (To maintain the horizontal director pointer centered requires a linear increase in aircraft pitch attitude until the aircraft pulls 4 g's after 2 seconds. The vertical director pointer is sensitive to roll and yaw deviations, and it will displace from center by an amount proportional to the deviation in roll and yaw.) When the aircraft reaches the preset release angle, the bomb is released automatically. At this time the LABS lamp goes out, the tone ceases, and the vertical director pointer deflects out of view, but the horizontal director pointer continues to be sensitive to g errors. The pilot, still holding the stores release button pressed, continues the Immelmann maneuver, keeping the horizontal director pointer centered. Upon completion of the maneuver, the stores release button is released, at which time the horizontal director pointer deflects out of view. After completing the run, the LABS-OFF-DIRECT switch is placed to OFF and the compass system controller mode switch is momentarily placed to SYNC.

TIMED OVER-THE-SHOULDER MODE.—This mode is essentially the same as the loft mode except that bomb release occurs at an aircraft pitch angle greater than 90° but less than 169.5°, and the pullup point is directly over the target. To execute the timed over-the-shoulder bomb run, follow the same procedures that apply to the loft bomb run except that the HIGH ANGLE control is used for setting the bomb release angle and TIMED O/S is selected on the bomb control panel.

INSTANTANEOUS OVER-THE-SHOULDER MODE.—The instantaneous over-the-shoulder mode does not require an identification point nor a timed interval. The instantaneous over-the shoulder bomb run is essentially the same as the timed over-the-shoulder run with the following exceptions: INST O/S is selected on the bomb control panel, the stores release button is pressed directly over the target, and pullup procedures are begun immediately.

PRINCIPLES OF OPERATION

Before discussing the principles of operation of the AN/AJB-7, the reader should be familiar with the block diagrams in figure 9-6 and 9-7. Figure 9-6 shows the block diagram of the all-attitude reference system, and figure 9-7 shows the block diagram of the bombing system.

Displacement Gyroscope Assembly

The displacement gyroscope assembly, the heart of the system, consists of a vertical gyroscope and a directional gyroscope, which are mounted within multiple, interacting gimbals; gyro torquers; pickoffs; and associated servo loops. All the components are mounted within a sealed container which also serves as the gyro frame. Figure 9-8 shows the gyros, gimbals, and associated servo loops.

VERTICAL GYROSCOPE.—The vertical gyroscope consists of the gyro spin motor B101, an inner roll gimbal, a vertical gyro pitch gimbal, an outer roll gimbal (common to both gyros), and the displacement gyroscope frame. The frame is mounted to the displacement gyroscope assembly case and, therefore,

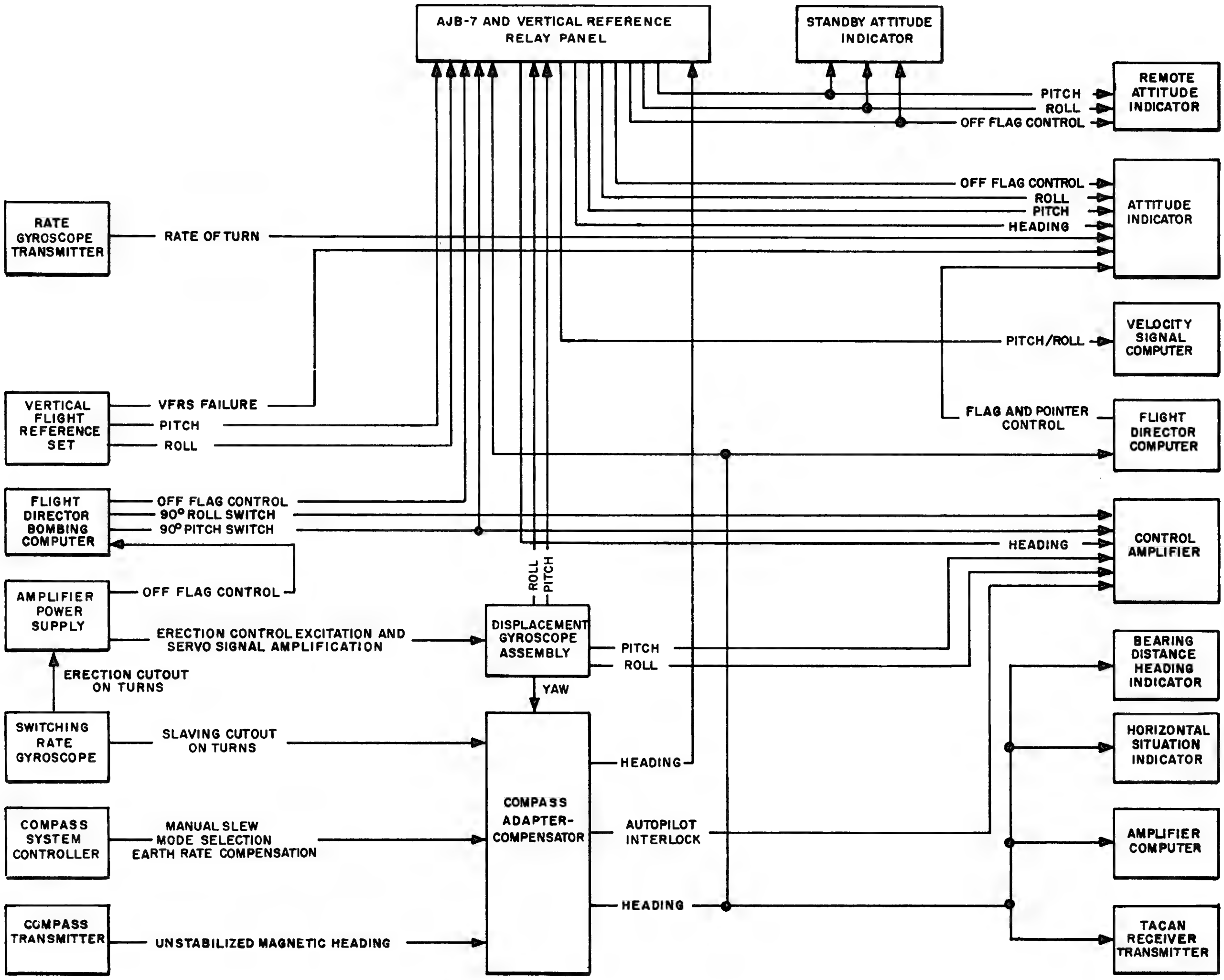

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Figure 9-6.—Block diagram of the all-attitude reference system.

follows all aircraft maneuvers. The outer roll gimbal, which is mounted in the frame, may rotate 360° about the roll axis, but it follows the aircraft in pitch and yaw. The vertical gyro pitch gimbal, mounted in the outer roll gimbal may rotate 360° about the pitch axis, but it follows outer roll gimbal movements in roll and yaw. The gyro spin motor may rotate ±85° in roll, but it follows the vertical gyro pitch gimbal in pitch and yaw. Mechanical stops (not shown) limit the movement of the inner roll gimbal to prevent alinement of the vertical gyro spin axis to the vertical gyro gimbal pitch axis. Such an alinement would cause the vertical gyro gimbal to spin about the pitch axis (gimbal lock).

DIRECTIONAL GYROSCOPE.—The directional gyroscope consists of the gyro spin motor B201, a leveling gimbal, an azimuth gimbal, and a directional gyro pitch gimbal. The directional gyro pitch gimbal, which is mounted in the outer roll gimbal, may rotate 360° about the pitch axis, but it follows the outer roll gimbal in roll and yaw. The azimuth gimbal, mounted in the directional gyro pitch gimbal, may rotate 360° about the yaw axis, but it follows the directional gyro pitch gimbal in pitch and roll. The directional gyro spin motor, B201, is mounted in the

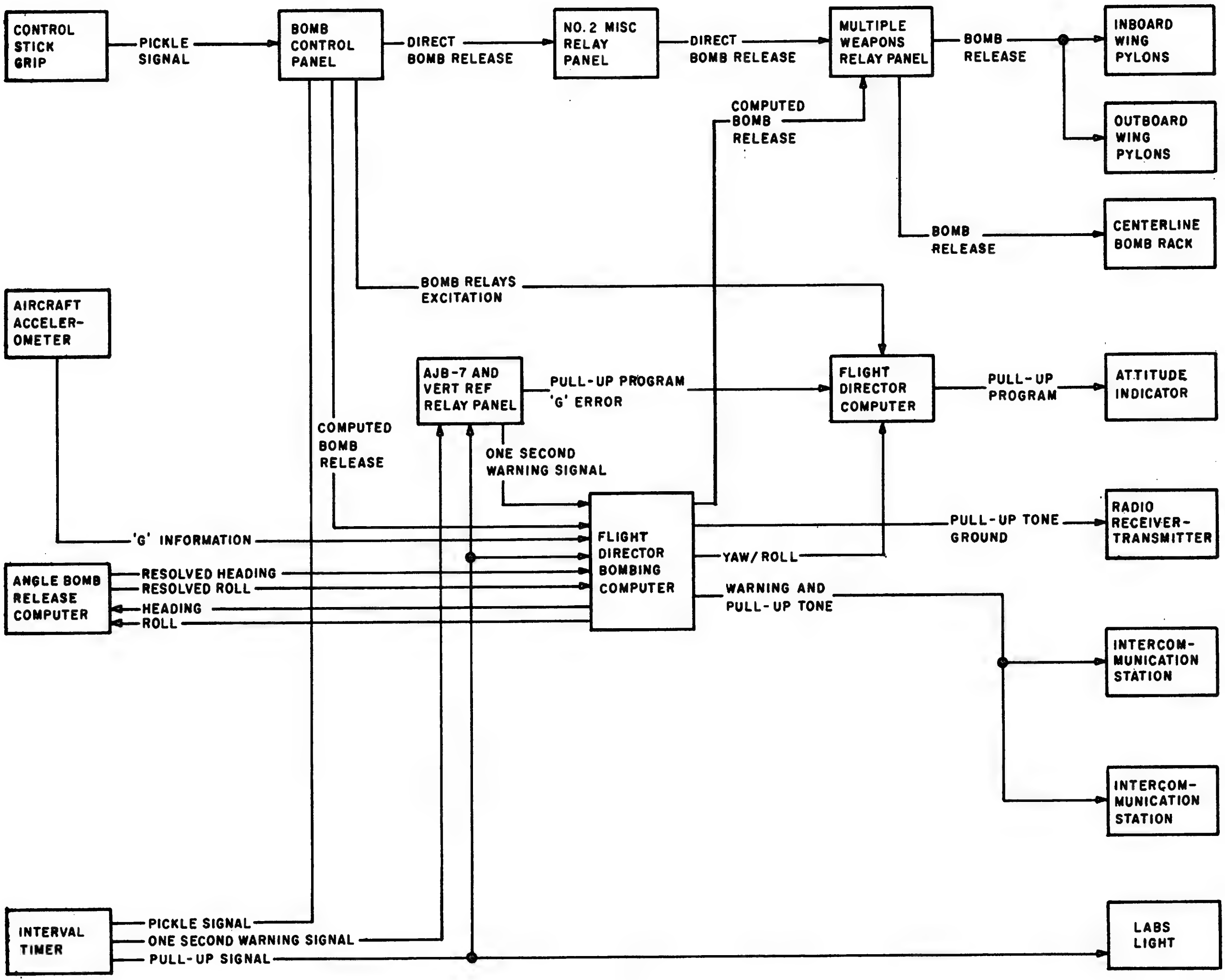

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Figure 9-7.—Block diagram of the bombing system.

azimuth gimbal; it may rotate ±85° about the roll axis. Mechanical stops (now shown) prevent gimbal lock.

GYRO START AND ERECTION CYCLE.— The purpose of the start and erection circuitry is to provide accurate pitch, roll, and azimuth information in the shortest possible time. The method in which this is done is discussed in the following sequence:

1. During the first 12 seconds after the application of power, the outer roll gimbal is driven or "caged" to a position which places the pitch gimbals of the vertical and directional gyros parallel to the aircraft pitch axis; the power OFF flag in the attitude indicator is in view; the spin motors of the vertical and directional gyros are accelerating slowly; vertical gyro pitch erection is taking place at a high rate, and directional gyro azimuth synchronization is occurring at a fast rate.

NOTE: Gyro spin motors are run at a slow rate to facilitate the fast pitch erection of the vertical gyro and the fast azimuth synchronization of the directional gyro. During this time interval, there is no pitch erection voltage applied to the directional gyro pitch torquers and no roll or leveling erection is taking place in either gyro.

2. From 12 to 60 seconds after application of power, the outer roll gimbal remains

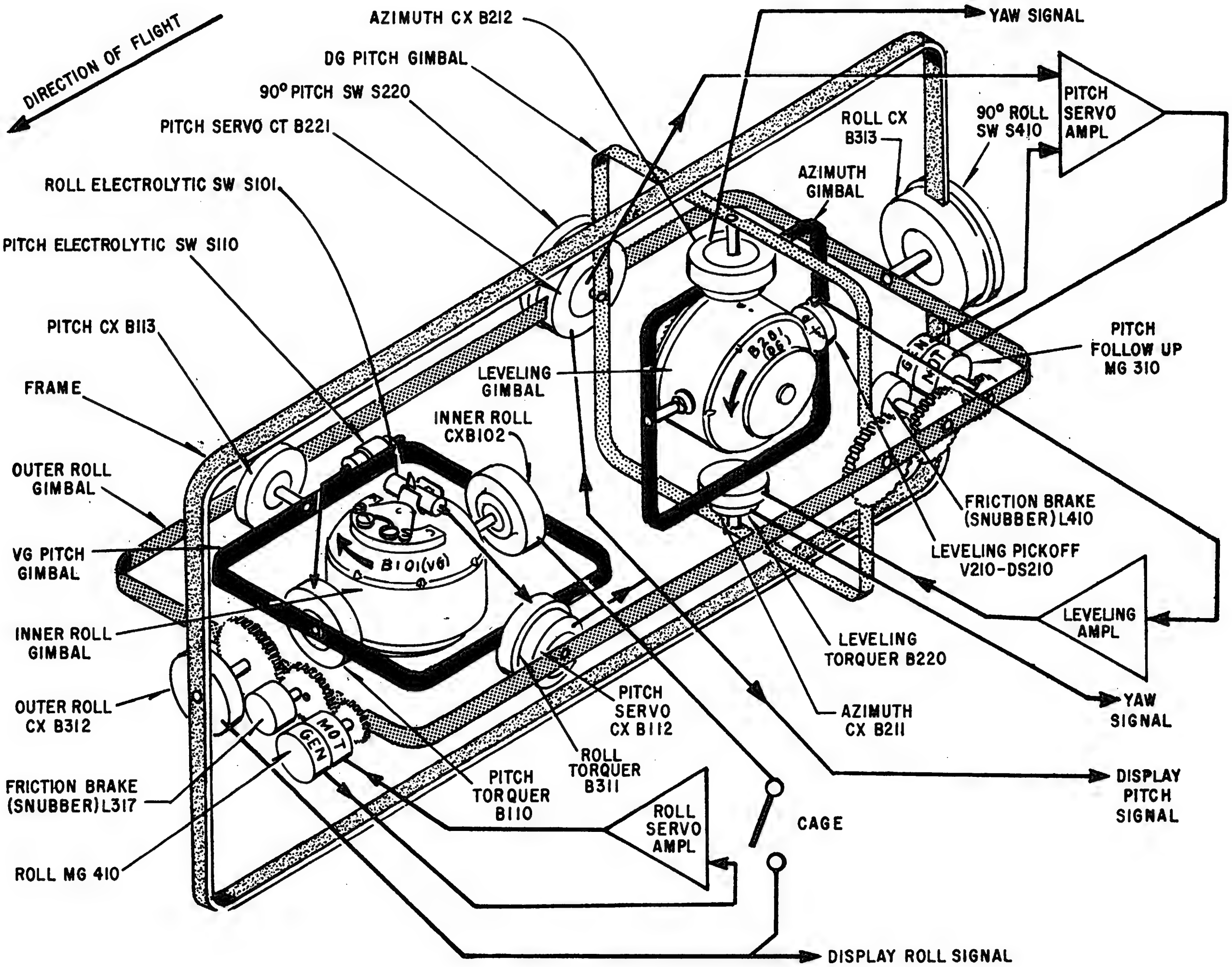

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Figure 9-8.—Displacement gyroscope assembly.

"caged"; the power OFF flag in the attitude indicator remains in view; full torque voltage is applied to the gyro spin motors; leveling erection occurs; high pitch and roll erection takes place; the directional gyro pitch gimbal is servoed to the vertical gyro pitch gimbal position; and fast azimuth synchronization is still taking place.

3. After power has been applied for 60 seconds—completing the start cycle—the outer roll gimbal is servoed to the inner roll gimbal position; the power OFF flag is deflected out of view; the spin motors continue to receive full torque voltage; leveling erection continues; and normal pitch and roll erection and normal azimuth synchronization take place.

Figure 9-9 is a chart illustrating the sequence of the displacement gyroscope start cycle.

GYRO LEVELING.—The vertical gyro roll and pitch erection circuits erect the spin axis of the vertical gyro to gravity-vertical by leveling the inner roll and vertical gyro pitch gimbals. Roll and pitch electrolytic switches, mounted on the inner roll and vertical gyro pitch gimbals respectively, sense unlevel conditions of the gimbals and activate torquers. The torquers precess the gyro to level the gimbal until the corresponding electrolytic switch is leveled.

The directional gyro leveling servo loop erects the spin axis of the directional gyro to a level position (horizontal). The leveling lamp

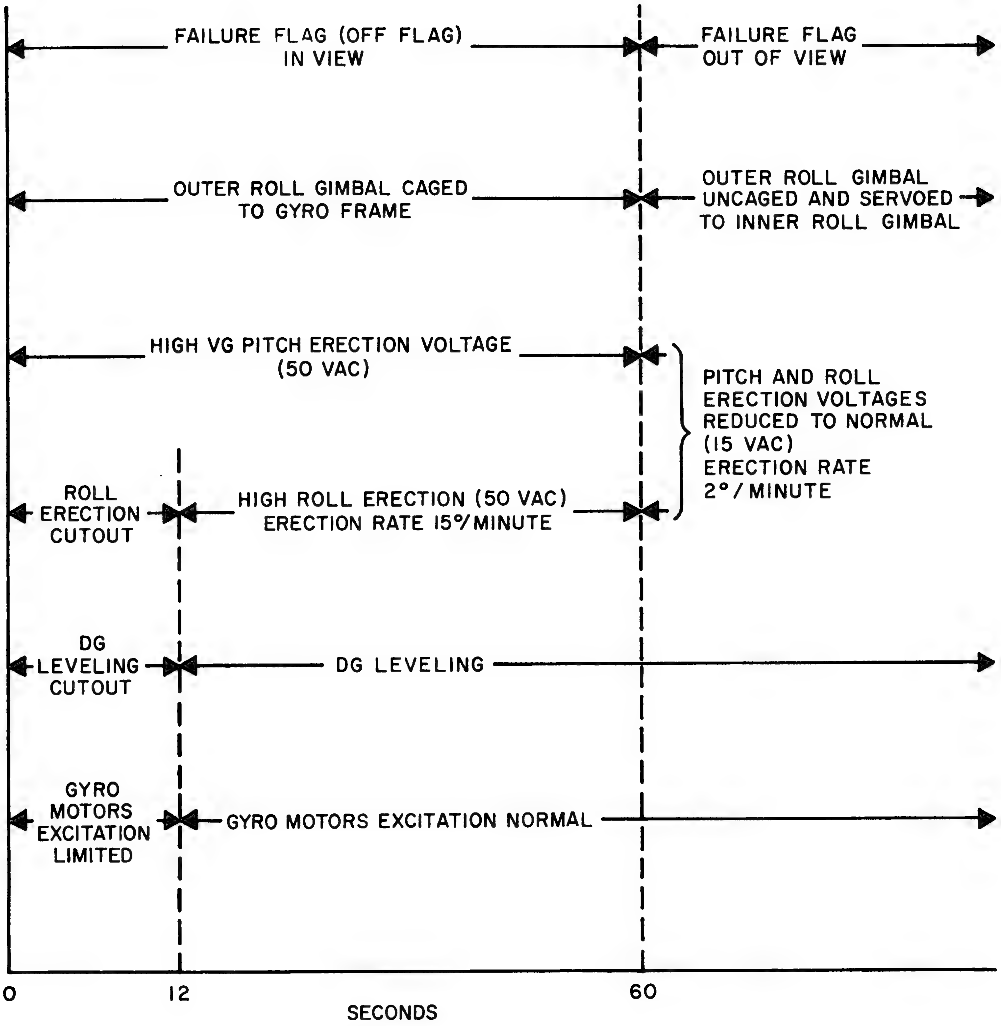

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Figure 9-9.—Displacement gyroscope start cycle.

DS210, mounted on the azimuth gimbal, activates the photocells through the shutter mounted on the directional gyro leveling gimbal. If the gimbal is not level, the photocells receive unequal amounts of light and apply different signals to the leveling modulator. The leveling modulator detects the difference and develops a signal which, when amplified, drives the leveling torquer in the direction required to level the gimbal. When the photocells receive equal amounts of light, there is no output from the leveling modulator.

The directional gyro pitch gimbal is servoed to the vertical gyro pitch gimbal so that their pitch gimbals are perpendicular to each other. Since the vertical gyro pitch gimbal is maintained horizontal to the surface of the earth, the directional gyro pitch gimbal is maintained perpendicular to the surface of the earth by maintaining its pitch gimbal perpendicular to the vertical gyro pitch gimbal.

DISPLACEMENT GYROSCOPE FAILURE WARNING.—A failure flag OFF indication in the attitude indicator will be produced, warning the pilot that his attitude information is unreliable under the following conditions:

1. A voltage at the tap of the vertical gyro spin motor B101 caused by loss or reduction of

one of the excitation phases or by a defective B101 winding.

2. A roll error signal obtained at the input of the roll amplifier which signifies that the outer roll gimbal is out of correspondence with the inner roll gimbal.

3. A pitch error signal obtained from the directional gyro pitch servocontrol transformer CT B211, signifying that the directional gyro pitch gimbal is out of correspondence with the vertical gyro pitch gimbal.

Attitude Indicating Functions

The following description of the attitude indicating functions is made under the assumption that the compass controller PRIM-STBY switch is in the STBY position. When the switch is in the PRIM position, the AN/ASN-70, instead of the displacement gyro, furnishes the attitude reference information.

INDICATOR ROLL SERVO LOOP.—The roll attitude reference signal is obtained from the displacement gyro roll control transmitter, CX B312, and applied to the attitude indicator roll control transformer. This signal contains information as to the amount and direction the aircraft is displaced from wings level. Since the rotor of the indicator roll control transformer is mechanically geared to rotate in coincidence with the indicator sphere, its output is indicative of the position of the sphere.

An aircraft bank displacement will produce an error signal in the rotor of the indicator roll control transformer which, in turn, is applied to the input of the roll amplifier located in the attitude indicator power supply. The output of the roll amplifier drives the motor of the roll motor generator, which is geared to the indicator sphere and the rotor of the roll control transformer, until the error signal in the roll control transformer is reduced to a null. This results in the servo loop being at rest in a new position with the sphere indicating the new bank position. The generator of the roll motor-generator provides an inverse feedback signal to the input of the roll amplifier which is proportional to the speed of the motor. This serves to damp the servo loop, providing maximum sensitivity without overshooting. A roll potentiometer is provided to compensate for any small errors in the servo loop or in the displacement gyro installation.

INDICATOR PITCH SERVO LOOP.—Operation of the pitch indicator servo loop is the same in principle as the roll servo loop. However, the pitch servo loop has an added function which is pitch trim fade. The pitch trim fade circuit offers a continuously variable pitch trim sensitivity which is maximum at 0° and 180° pitch attitude and zero at the 80° climb and dive attitudes. Included in the pitch trim fade circuit is the PITCH TRIM resistor, which is an operating adjustment mounted at the front of the attitude indicator. The PITCH TRIM control is used to adjust the sphere to a zero pitch indication for easy pilot reference whenever a positive or negative angle of attack must be assumed in order to maintain a constant cruise altitude. The purpose of the pitch trim fade circuit is to gradually and smoothly remove the effects of the trim setting on the indicator pitch presentation when the aircraft goes into a climb or dive maneuver.

The pitch trim fade resistor is variable through 360°, and it is geared to the pitch servo train. Its output is transformer coupled across the PITCH TRIM potentiometer. At 0° and 180° pitch, maximum voltage is coupled across the PITCH TRIM potentiometer; and at the 80° points, the voltage across the PITCH TRIM potentiometer is zero.

INDICATOR AZIMUTH SERVO LOOP.—Operation of the azimuth servo loop is the same as the roll loop except that it receives its input information from the azimuth control differential transmitter CDX B208 located in the compass adapter. CDX B208 receives an electrical input from the displacement gyro azimuth synchro and a mechanical input from the compass adapter slaving and correction servomotor. The compass adapter function is explained in the discussion on the azimuth system.

Azimuth System

In the following discussion on the azimuth system, refer to figure 9-10.

FREE MODE OPERATION.—In the free mode (DG mode) of operation, only gyro azimuth information is displayed on the attitude indicator sphere. In this mode, a heading reference is obtained by manually slewing the attitude indicator to the desired heading by the SET HDG switch on the compass controller. Apparent and real drift compensating circuitry is utilized in the free mode of operation to minimize the effects of known directional gyro drift errors.

Referring to figure 9-10, note that two azimuth transmitters, CX B212 and CX B211, in the displacement gyroscope supply azimuth

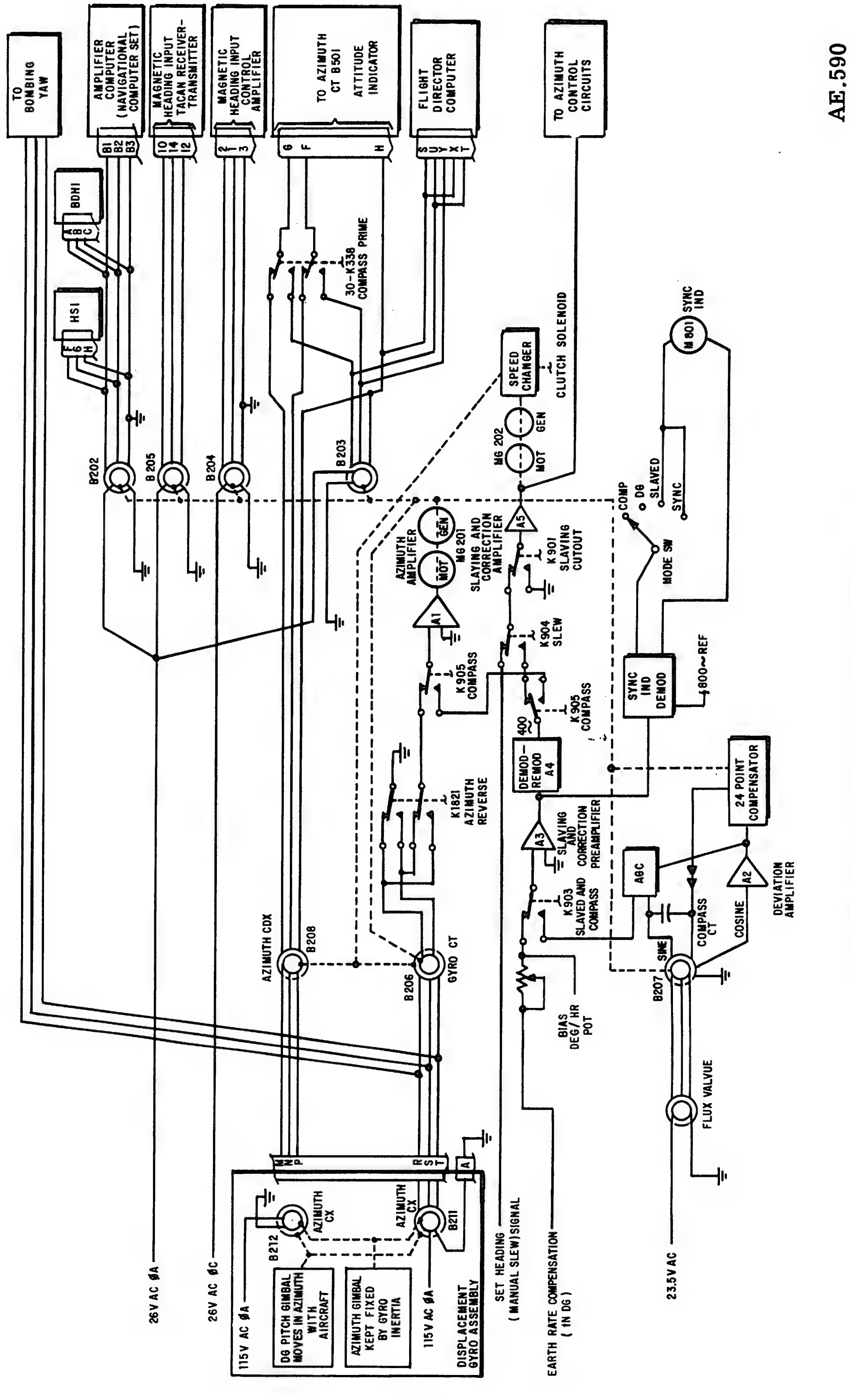

Figure 9-10.—Azimuth channel servo loops.

information to the compass adapter. Azimuth control transmitter CX B212 supplies azimuth information to the attitude indicator azimuth servo loop through the azimuth control differential transmitter CDX B208. In free mode operation, CDX B208 has a mechanical input to its rotor which is compensation for directional gyro drift.

Azimuth control transmitter CX B211 supplies directional gyro azimuth information to the gyro actuated servo loop within the compass adapter. The gyro actuated servo loop provides a number of functions which are now discussed in detail.

Gyro Actuated Servo Loop.—If the mechanical rotor-stator relationship of gyro control transformer CT B206 in the compass adapter is not in correspondence with the rotor-stator relationship of azimuth control transmitter CX B211 in the displacement gyro, an error signal will be applied to the input of azimuth amplifier A1. The push-pull output of amplifier A1 is applied to the control winding of the 2-phase servomotor of azimuth motor-generator MG201. The output of the motor is geared to heading data transmitters B202, B203, B204, and B205; to the wiper of a distributor potentiometer, which is the 24-point compensating network for the flux valve; to the rotor of compass control transformer CT B207; and to the rotor of gyro control transformer CT B206. Also connected to the motor shaft is the shaft of the velocity generator section of MG201. The generator develops a voltage proportional to motor speed. The generator output voltage is fed back to the input of amplifier A1 180° out of phase with the error signal, serving to damp the servo loop.

Assuming that the aircraft is initially in straight and level flight with the servo loop at rest, the rotor-stator relationship of B206 will be coincident with the rotor-stator relationship transmitted electrically by B211. If the aircraft now makes a 30° heading change, this change in position between the stable directional gyro and the aircraft will be measured by B211 and transmitted to B206. As the aircraft turns, the error signal output from B206 is amplified by azimuth amplifier A1 and drives MG201. This drives the rotor of B206 to track very near the null, lagging just enough to maintain sufficient error signal to keep the servo loop energized. At the completion of the 30° heading change, the data shaft has moved 30° and MG201 stops. The heading data transmitters indicate the new heading.

Gyro Drift Compensation.—The directional gyro, and therefore the reference signal from B206, is subject to two types of drift—real and apparent. Real drift is caused by mechanical imperfections in gyro construction. Apparent drift is caused by rotation of the earth about the "space reference" gyro gimbal. Both types of drift are compensated for to a large extent by driving the stator of B206 and the rotor of CDX B208 in the direction and at the rate required to counteract the drift.

The signal for compensating "real" drift is obtained by setting the zero-center BIAS DEG/HR adjustment control on the compass adapter to the dial indication equal in magnitude but opposite in direction to the known directional gyro drift. The signal for compensating apparent drift is obtained at the LAT control on the compass controller, whose dial is calibrated from 0° to 90°, since the apparent drift is proportional to the sine of the latitude. The direction of apparent drift is opposite in the two hemispheres; therefore, the N-S switch is provided on the compass controller to reverse the phase of the latitude compensation signal.

The real drift signal and the apparent drift signal, along with the feedback signal from the output winding of the velocity generator of slaving and correction motor-generator MG202, are summed and applied through closed contacts of relay K903 to the input of slaving and correction preamplifier A3. The resultant signal is amplified by A3, stripped of quadrature voltages by slaving and correction demodulator-remodulator A4, and applied through the closed contacts of relays K905, K904, and K901 to the input of slaving and correction amplifier A5. The push-pull output of A5 is applied to the control winding of slaving and correction servomotor MG202. MG202 drives the stator of B206 and the rotor of B208 through a speed decreaser at a speed proportional to the applied correction signal.

SLAVED MODE OPERATION.—In the slaved mode of operation, the gyro-actuated servo loop remains the same as that for free mode operation. The slaved mode operation differs in that the actuating signal for the servo loop which drives the stator of B206 is a magnetic heading signal from the flux valve. This servo loop is called the slaving loop in slaved mode operation and is a closed loop; that is, it is mechanically linked back to the gyro-actuated servo loop.

Heading information from the earth's magnetic field is fed from the flux valve to the

rotor of B207, which is the compass control transformer located in the compass adapter. CT B207 has two stator windings which are wound 90° apart. The error signal, which is applied to the slaving and correction preamplifier A3 through the AGC circuitry, is a sine function, while the signal applied to the deviation amplifier A2 is a cosine function; that is, it is maximum when the error (sine) signal is minimum.

Because of the saturation characteristics of the flux valve, the error signal applied through closed contacts of relay K903 and amplified by slaving and correction amplifier A3 is at a frequency of 800 Hz. This 800-Hz signal must be converted to a line referenced 400-Hz signal in order to operate the slaving and correction motor MG202. The required conversion is accomplished by slaving and correction demodulator-remodulator A4. The 800-Hz signal is demodulated to direction sensitive d.c., which in turn is remodulated to provide a phase sensitive 400-Hz a.-c. signal signal at the output. The output of A4 is applied through closed contacts of relays K905, K904, and K901 to the input of slaving and correction amplifier A5, where it is amplified, actuating slaving and correction motor MG202. MG202 drives the stator of B206 and the rotor of B208 through the speed decreaser.

Automatic Gain Control.—The magnetic field intensity varies at different geographical locations, causing variations in the error signal for the same given amount of error. During normal slaved mode operation, the voltage induced in the cosine winding is proportional to the magnetic intensity level. This signal is applied to the AGC network, thus providing maximum attenuation of the error signal for strong magnetic intensity levels and minimum attenuation for weak magnetic intensity levels, accomplishing a relatively constant overall sensitivity.

Flux Valve Compensation.—Flux valves contain tracking errors which cannot be completely eliminated by indexing and magnetic compensating adjustments. In order to further reduce the magnetic heading error, an electrical 24-point flux valve compensating network is employed. The network consists of a 360° continuous distributor potentiometer which is mechanically linked to the data shaft, and 24 deviation compensation adjustment potentiometers connected across the output of deviation amplifier A2 with their wipers connected at 15° intervals about the distributor potentiometer. The amount and direction of deviation compensation set in at a given 15° interval is dependent upon the distance and direction that the applicable deviation compensation potentiometer is moved from center.

If a fixed excitation voltage for the network were used, the deviation compensation portion of the signal applied to slaving and correction preamplifier A3, and thence the amount of correction, would vary with field strength. In order to keep the correction sensitivity constant, therefore, the network excitation is derived from the output of deviation amplifier A2, which is proportional to field strength.

Slaving Action.—Assuming that the directional gyro has drifted out of correspondence with the magnetic heading reference, the data shaft will tend to drive to this false reference. However, the rotor of compass CT B207 is linked to the data shaft and is rotated an equal distance. This causes an error signal at the input to the slaving loop, which actuates slaving and correction servomotor MG202, driving the stator of B206 in the direction to reduce the error resulting in the data shaft being driven back into correspondence with the magnetic heading reference. In practice, the slaving loop is so tight that the data shaft does not get perceptibly out of correspondence with the magnetic heading signal, except during turns when slaving is interrupted by the switching rate gyro.

When the aircraft turns, no slaving takes place. If, for example, the aircraft makes a 30° heading change, the gyro-actuated servo loop will drive the data shaft, and thence the rotor of B207, 30°. However, the flux valve, being mounted to the airframe, rotates 30° in the earth's flux field, keeping the input signal to the slaving loop at null.

Fast Synchronization and Slewing.—During normal slaving operation, the output of the slaving and correction servomotor is geared down approximately 43,000 to 1 by the speed decreaser. When the speed decreaser is energized, the gear ratio is changed to approximately 12 to 1, which greatly increases the speed of rotation of the stator of B206 and the rotor of B208 for a given output from the slaving and correction amplifier. The speed decreaser is energized whenever SYNC is selected by the compass controller mode switch or whenever manually slewing by the SET HDG switch on the compass controller.

Fast synchronization is effected automatically during the start cycle or whenever the heading

mode is switched from DG to slaved. Fast synchronization may also be initiated manually by momentarily placing the compass controller mode switch in the SYNC position when in the slaved mode. When switching from the DG mode to the slaved mode, fast synchronization will continue until the error signal is reduced to a very small value, at which time normal slaving will resume. Momentarily placing the compass controller mode switch to SYNC will also produce fast synchronization which continues until the slaving error signal has been reduced to a very small value, as for automatic fast synchronization.

Slewing is initiated by depressing the SET HDG knob on the compass controller. This deenergizes relay K904, shifts the speed decreaser into high speed operation, and connects the wiper of the SET HDG potentiometer to the input of the slaving and correction amplifier. The slewing direction and speed is dependent on the direction and distance the knob is turned from center.

COMPASS MODE OPERATION.—In the compass mode of operation, directional gyro azimuth control transmitter CX B211 is disconnected from the azimuth (MG201 actuated) servo loop and flux valve heading information is connected in its place. When the compass mode is selected, compass relay K905, free-slave relay K903, and the automatic pilot cutout relay K907 are energized. The flux-valve-actuated circuitry is the same as for the slaved mode of operation up to the output of demodulator-remodulator A4. In the compass mode, azimuth CT B211 is disconnected from the input of azimuth amplifier A1; the A4 output, instead of being connected to the input of slaving and correction amplifier A5, is connected to the A1 input. The motor of MG201 will drive compass CT B207 to null out any loop error signal. This loop is a highly sensitive loop compared to the slaving loop, which is operated through a large ratio gear reduction. Since the response is instantaneous, no SYNC IND meter indication or fast synchronization is required.

The attitude indicator azimuth servo loop, in compass mode operation, receives heading information from the output of heading data control transformer CT B203, instead of CDX B208.

Automatic Pilot Cutout.—The automatic pilot is decoupled from the azimuth system (1) when operating in the compass mode, (2) when the SET HDG knob is depressed, and (3) during fast synchronization.

BOMBING FUNCTIONS AND SPECIAL SWITCHING

Loft Bombing Run

INITIAL CONDITIONS.—To set in the initial conditions for a loft bomb run, place the switches on the bomb control panel to the following positions: LABS, READY, and LOFT. Switching contacts are also closed in the multiple weapons relay panel to complete the circuit from the bomb release switch (pickle button) to the interval timer, which will begin rundown when the pickle button is depressed.

CIRCUIT CONDITIONS AFTER DEPRESSING PICKLE BUTTON.—Depressing the pickle button applied a 28-volt d-c signal to the interval timer and rundown begins immediately. The 28-volt pickle signal is also applied to the flight director bombing computer, causing switching which disconnects the horizontal and vertical flight director pointers from the biasing supply, and allowing them to be deflected to the center of the attitude indicator. One second before pullup time out, the interval timer supplies a ground for the 1-second warning relay which supplies a quarter second 28-volt d-c pulse to energize the tone relay in the flight director bombing computer which applies a 1200-Hz tone in the headsets.

CIRCUIT CONDITIONS AFTER PULLUP.—At the end of the preset time interval, the timer provides a 28-volt d-c signal which energizes the LABS lamp; energizes the tone generator which produces a steady tone until the bomb is released or canceled; energizes the displacement gyroscope cage control relay which switches the input of the roll servo loop to the inner roll synchro; starts the g programer which furnishes pullup information to the horizontal director pointer; and switches azimuth information to the vertical director pointer. The pullup signal is also applied to one side of the low angle and high angle release switches in the release angle computer, but the switches are open so no release occurs at this time.

Figure 9-11 shows the block diagram of the loft bombing functions from pullup to bomb release.

Referring to figure 9-11, during the interval between pullup and bomb release, the loft bombing circuitry may be considered as performing the following two primary and independent functions:

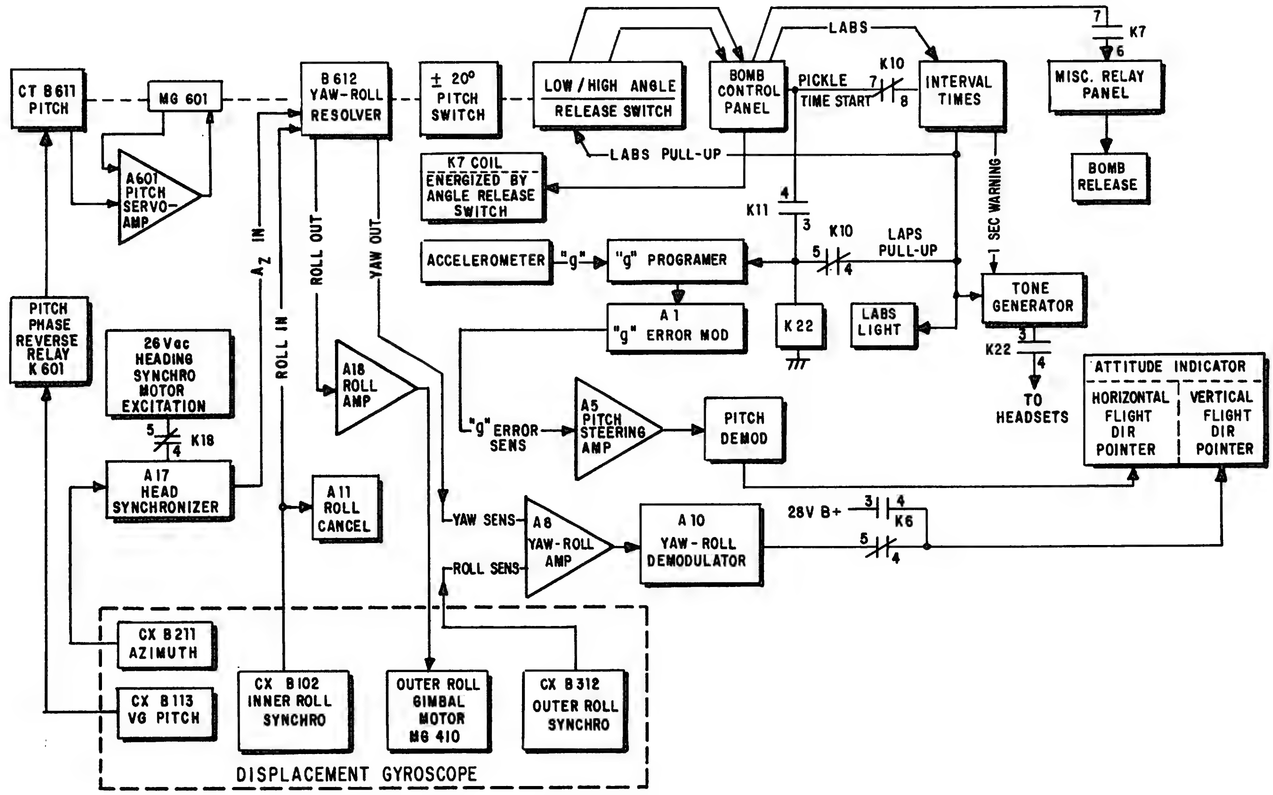

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Figure 9-11.—Block diagram of loft bomb circuit functions at pullup.

1. Operation of the horizontal director pointer, which supplies the pilot with pullup information.

2. Operation of the vertical director pointer, which supplies the pilot with roll-yaw attitude information.

Horizontal Flight Director Pointer Operation.—The g programer begins operation when it receives the pullup signal from the interval timer, and it continues until the pickle switch is released. During the first 2 seconds after pullup, the g programer gradually increases a programed 1-g signal to a 4-g signal. After the initial 2 seconds, the signal level is maintained at 4 g's throughout the remainder of the maneuver. The g level being experienced by the aircraft as sensed by the accelerometer is compared to the programed g level. The resultant is applied to the input of g error modulator A1. The g error modulator converts the signal to a 400-Hz a-c signal and then applies it to pitch steering amplifier A5 where it is amplified and passed on to pitch demodulator A3. The signal is demodulated by A3 and applied to the horizontal flight director pointer in the attitude indicator. In order to keep the pointer centered, the pilot must enter into the loop as programed, then must hold 4 g's until inverted flight is reached. If the g force as sensed by the accelerometer is less than the programed "g force," the pointer will rise above center; if the accelerometer sensed "g force" is greater than the programed "g force," the pointer will move below center.

Vertical Flight Director Pointer Operation.—The vertical flight director pointer is controlled by the gimbal action in the displacement gyroscope assembly. As the pitch angle is increased, the displacement gyro inner roll gimbal becomes less sensitive to aircraft roll and more sensitive to yaw. At the same time, the azimuth gimbal becomes less sensitive to yaw and more sensitive to roll, until at 90° pitch the inner roll gimbal would sense pure yaw and the azimuth gimbal would sense pure aircraft roll. In order to provide accurate roll and yaw signals during

bombing maneuvers, the information from the inner roll and azimuth synchros is resolved as a function of aircraft pitch angle. This is accomplished by yaw-roll resolver B612 whose rotor is mechanically linked to the release angle computer pitch servo loop.

Pitch CT B611 in the release angle computer receives its input signal from the VG pitch CX B113 through contacts of the pitch phase reverse relay K601. The B611 rotor output drives pitch motor MG601 via pitch amplifier A601. Loop damping is provided by the MG601 rate generator section. The rotor of CT B611 is geared to MG601; and as the motor drives to keep the CX output signal at null, it also keeps the loop data shaft in correspondence with the aircraft pitch attitude. Geared to this shaft are the high angle and low angle bomb release switches and yaw-roll resolver B612.

The resolver is effectively a variable coupling transformer with two windings (inner roll and azimuth) on its rotor and two windings (roll and yaw) 90° apart on its stator. An input signal may be applied to each rotor winding and an output signal may be taken off each stator winding. Since the rotor of the resolver is linked to the pitch data shaft, the signal induced in each stator winding is a mixture of the two input signals as a function of pitch angle. At zero pitch attitude, the roll signal induced in the roll stator winding is maximum and the azimuth signal is minimum while the roll signal induced in the azimuth stator winding is minimum and the azimuth signal is maximum. At 90° pitch attitude, the reverse is true. However, provisions are made to keep the inner roll signal from affecting the azimuth synchronizing loop.

During all-attitude operation, the outer roll gimbal is slaved directly to the inner roll gimbal as previously explained. If an Immelmann maneuver were performed, the outer roll gimbal would have been driven 90° as the aircraft approached vertical flight and an additional 90° shortly after the aircraft passed through vertical flight. The reason for this is that as the outer roll gimbal pitch attitude changes, it must be driven further and further to null out any slight aircraft yaw, until it must be driven 90° as vertical flight is reached. The inner roll sensing reverses as the aircraft passes through vertical flight, causing the outer roll gimbal to be driven an additional 90° while moving toward inverted flight. After rollout the outer roll gimbal is positioned the same relative to both the aircraft and the earth as it was prior to the performance of the Immelmann maneuver. Because of the 180° rotation of the outer roll gimbal when going from level flight to inverted flight, the resultant pitch signal would approach 90°; and instead of moving through toward 180°, it would return toward zero. This condition is acceptable for operating the attitude indicator sphere, since the sphere would rotate 180° in roll, providing the same effect as a 180° rotation in pitch.

However, LABS bombing operations require a continuous pitch signal throughout the maneuver until the bomb is released; therefore, the outer roll gimbal must be maintained level in roll. The actuating signal for the displacement gyro roll servo loop, instead of being applied directly from inner roll CX B102, now comes from the combination of roll and azimuth information present in the B612 roll output winding via roll amplifier A18.

Since any errors present during the maneuver in either roll or yaw are corrected by rolling the aircraft, the two signals are mixed together and applied to the attitude indicator vertical director pointer as a high sensitivity error display. The roll signal is obtained from outer roll CX B312 in the displacement gyro. This signal is applied to the input of the yaw-roll amplifier A6.

The yaw error signal is obtained from the yaw output winding of yaw-roll resolver B612 and applied to amplifier A8. In amplifier A8, the two signals are mixed and the resultant is amplified before being transformer coupled to the input of yaw-roll demodulator A10. In the demodulator, the signal is converted to a direction sensitive d.c. before being applied through contacts of bomb cancel relay K6 to the vertical director pointer.

Immediately before pullup, the pilot assumes the required heading. This is the reference attitude from which any subsequent azimuth deviations are sensed. The yaw input to the yaw-roll resolver B612 is obtained from the azimuth synchro B212 via heading synchronizer A17. Before pullup, the heading synchronizer servo loop is completed and any heading change sensed by CX B212 is nulled out at the heading synchronizer CT rotor, maintaining the required zero reference. At pullup, relay K18 energizes, removing the excitation voltage from the heading synchronizer motor, which deactivates the servo loop. Now, any deviation from the reference azimuth attitude will appear as a signal in

the azimuth input winding of resolver B612. The pilot must correct this condition to return the vertical flight director pointer to center.

The signal from the inner roll synchro B102 is coupled to the roll cancel relay driver A11. If the aircraft yaws 30° or more as it approaches vertical flight, this signal will be large enough to increase the A11 output impedance sufficiently to deenergize the roll cancel relay, which in turn energizes the bomb cancel relays, thus canceling automatic bomb release. Releasing the pickle button any time after pullup will also cause bomb cancel. In either case, the LABS lamp goes out and the 1200-Hz tone ceases.

CIRCUIT FUNCTIONS AFTER BOMB RELEASE.—As the aircraft increases its pitch attitude, the low angle switch is driven correspondingly by the pitch data shaft in the release angle computer. Upon reaching the preset release angle position, the switch applies 28 volts d.c. to the bomb release relay K7. This applies the 28-volt bomb release signal to the miscellaneous relay panel which effects a release through the safe-ready switch of the bomb control panel. The LABS lamp will go out due to switching in the same relay panel. This switching action will also cause the 1200-Hz tone in the headsets to cease.

Energizing the bomb release relay K7 also energizes the bomb cancel relays K6 and K10. Once K6 and K10 are energized, they remain energized by hold in contacts connected to the pickle line. Energized K10 removes power from the clutch and motor of the interval timer, allowing it to reset. Contacts 4 and 5 of K10 are open, removing the 28-volt d-c pullup signal from the programer start relay K11, which is not deenergized at this time since it is held connected to the pickle line through its own contacts 3 and 4. The switching action, as a result of energizing K10, also restores displacement gyro roll and pitch erection and azimuth system slaving; disconnects the roll output of yaw-roll resolver B612 from the displacement gyro outer roll gimbal servo loop; deactivates the roll input to yaw-roll amplifier A8; and reactivates the heading synchronizer loop.

Energizing K6 switches the vertical flight director pointer from the yaw-roll demodulator to the 28-volt d-c line, which deflects the pointer from view.

Resetting of the timer removes the 28-volt d.c. from the section of the pullup line not already broken by the contacts of K10. The cage relay and the bomb release relay are thus deenergized. The inner roll signal is reconnected to the input of the displacement gyro servo loop, referencing the outer roll gimbal directly to the inner roll gimbal. The computer set now has been returned to an all-attitude mode, except that the horizontal pointer display remains so that the pilot may complete his Immelmann maneuver.

Since bomb release (and therefore bomb cancel and return to all-attitude operation) occurs at a pitch angle less than 90°, it is unlikely that the DG pitch gimbal has gone through 90° pitch. Assuming that it does not, no change of state of the pitch segment switch will occur. However, the outer roll gimbal will rotate 180° while going through vertical flight, causing the roll segment switch to change state. After rollout, the roll segment switch will return to its original state.

Release of the pickle button removes the energizing voltage from relays K6, K7, and K10, and the horizontal flight director pointer is deflected out of view. All-attitude operation is now fully restored.

Instantaneous and Timed Over-the-Shoulder Bombing Runs

In comparison to the loft method, no identification point or timed interval is used in the instantaneous over-the-shoulder mode. The pilot simultaneously depresses the pickle button and starts pullup. For this reason the pullup line is connected to the pickle line through the INST O/S switch contacts of the bomb control panel. Otherwise, circuit conditions prior to and immediately after pullup for both instantaneous and timed over-the-shoulder modes are identical to the loft method.

Both modes differ from loft in that bomb release and therefore bomb cancel occur after the aircraft has passed through 90° pitch angle. This has no significance, except for release angle, as far as the bombing circuitry is concerned. Its significance is effected in the displacement gyro gimbal action and the resulting switching.

In the loft mode, the DG pitch gimbal does not go through 90° due to the 180° rotation of the outer roll gimbal. In the instantaneous and timed over-the-shoulder modes, the loop reference signal remains resolved to give true aircraft roll information through 90°. Therefore, no rotation takes place.

If the outer roll gimbal—before starting the run—is in the position shown in figure 9-8, it is necessary to energize three relays in order to energize the pitch and yaw phase reverse relay, K4. These are the 90° pitch relay K17, the 90° roll relay K5, and the ±20° pitch relay K12.

When the aircraft reaches vertical flight, the pitch segment switch will provide a ground, energizing the 90° pitch relay K17. Energizing K17 fulfills one of the three conditions required to energize the pitch and yaw phase reverse relay K4. Also, energizing K17 deenergizes the azimuth phase reverse relay which, in turn, reverses the sensing of the compass adapter azimuth servo loop to correct for the displacement gyro azimuth synchro not sensing the 180° heading change when the aircraft passes through vertical flight. The attitude indicator displays the opposite side of the sphere at this time, automatically presenting the proper heading.

Upon releasing the bomb (assuming a release angle greater than 90°), direct control of the outer roll gimbal is returned to the inner roll gimbal. Inversion of the outer roll gimbal in pitch causes a sense reversal between inner and outer roll gimbals. To keep the outer roll gimbal from driving 180° because of this sense reversal, phase reversing of the inner roll signal is effected at this time. This is accomplished by the open contacts of the now deenergized cage relay K14, which removes 28 volts d.c. from the coil of the roll phase reverse relay K13.

The aircraft continues the inside loop until inverted flight is reached, then rolls out. When 90° bank angle is attained, the roll segment switch will provide a ground, energizing the 90° roll relay K5, which fulfills the second of the three requirements for energizing the pitch and yaw phase reverse relay K4. If the maneuver has been correct, the aircraft will be well within the limits of the ±20° pitch segment switch providing an energizing path to ground for the ±20° pitch relay K12. This fulfills the third condition required for energizing relay K4. Contacts of K4 in turn apply 28 volts d.c. to energize pitch reverse relays K8 and K601 and yaw phase reverse relay K19. Contacts of these relays provide proper phasing to the input of the pitch steering circuit, the bomb release angle computer pitch servo loop, and the heading synchronizing servo loop, respectively. This establishes proper phasing for the next bombing run.

Relay K4 will remain energized until another high angle release bomb run is completed, since it is held in by normally open contacts of K17 and K5 and normally closed contacts of K12, all in parallel.

Direct Bombing Run

The direct method does not require computer set switching. Direct method is selected on the bomb control panel and, when the pickle button is actuated, bombs are released at that point.

Description of System Tie-In

The vertical reference set furnishes pitch and roll information to the computer set when the controller PRIM-STBY switch is in PRIM, except that during bombing functions the computer set displacement gyro becomes the primary reference. When the PRIM-STBY switch is in STBY the displacement gyro is the attitude reference for both all-attitude and bombing functions.

The remote attitude indicators use the displacement gyro as a reference in both positions of the PRIM-STBY switch. Their input signal phase in both roll and pitch is reversed if the position of the displacement gyro DG pitch gimbal requires it. The phase reversal is accomplished by roll and pitch transformers in the aircraft relay panel operating in conjunction with the displacement gyro DG pitch gimbal 90° pitch switch, the pitch phase reverse relay in the flight director bombing computer, and phase reversing relay in the aircraft relay panel.

Magnetic heading information is sensed by the flux valve and applied to the compass adapter. The compass adapter sends compensated magnetic heading information to the bearing-distance-heading indicator (BDHI), the horizontal situation indicator (HSI), the amplifier computer, the flight director computer, and the control amplifier.

The BDHI and the HSI present a compass card display. The amplifier computer converts the magnetic heading information to true heading. The flight director computer uses the heading information for bomb mode operation.

The control amplifier provides attitude reference signals to the automatic flight control system autopilot. It contains relays which are operated by the 90° pitch and 90° roll switches in the displacement gyro to provide correct output signal polarity. An interlocking signal from

the computer adapter removes the compass adapter heading signal when it is erratic.

Depressing the bomb release switch (pickle button) releases the bombs immediately when in the direct bombing mode if the SAFE, READY switch is in the READY position. The LABS light does not light in the direct mode delivery method.

VERTICAL FLIGHT REFERENCE SET AN/ASN-70

The Vertical Flight Reference Set (VFRS) AN/ASN-70 currently in use on the F-4J aircraft furnishes aircraft pitch and roll attitude, flightpath angle, and vertical acceleration information on the F-4J weapons system.

The reference set has been developed to provide the necessary verticality for highly accurate attitude sensing during dynamic flight conditions. Longitudinal and lateral accelerations, which normally cause errors in gravity-sensing vertical gyroscope erection systems, are compensated for in the reference set.

COMPONENTS OF SYSTEM

The vertical flight reference set (fig. 9-12) consists of two units—the vertical flight reference sensor and the vertical flight reference computer. The sensor is mounted on top of the computer to conserve space and wiring.

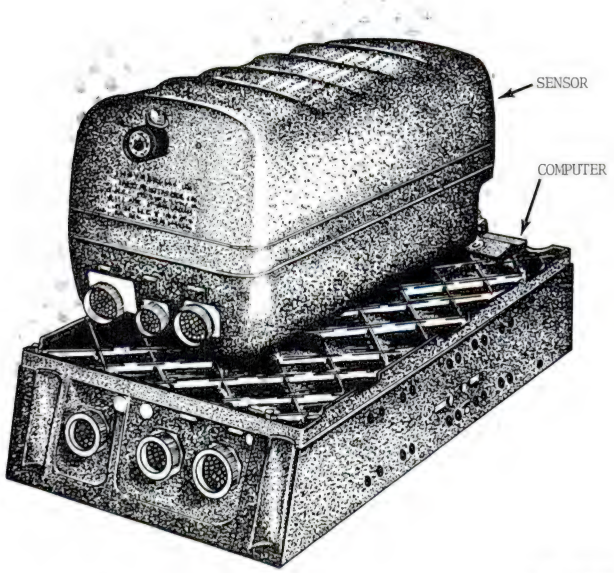

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Figure 9-12.—Vertical Flight Reference Set AN/ASN-70.

The sensor is a hermetically sealed unit containing a vertical gyroscope (gyro) and a geocentric pendulum control (pendulum) in a common roll gimbal (fig. 9-13). The pendulum is stabilized in pitch by a pitch gimbal which is servoed to the gyro. The pendulum provides the necessary erection signals to the vertical gyro torquers to maintain the gyro at true vertical. A roll and pitch stabilized vertical accelerometer mounted in the sensor provides an output of vertical acceleration which is available for other subsystems and is used by the computer for flightpath angle computations.

The computer is a nonhermetically sealed unit containing all necessary electronics for operation of the reference set. Circuitry and mechanization is provided for flightpath angle and vertical velocity computation. The computer circuitry is arranged in modular form for easy maintenance.

The computer has twelve plug-in sealed modules and 10 repairable printed circuit boards. The printed circuit boards are wired into the chassis circuits through stud terminals but may be displaced sufficiently to provide access to the mounted components.

FUNCTIONAL DESCRIPTION

Geocentric Pendulum

The pendulum is the vertical sensor of the reference set. Unlike conventional gravity sensors, it is not subject to verticality errors caused by longitudinal and lateral accelerations. Basically, the pendulum is a pendulous gyroscope with a variable speed spin motor. With this configuration, the pendulum can compensate for accelerations due to changing aircraft airspeed and turns.

Longitudinal accelerations occur as the aircraft airspeed changes as a result of changes in engine power setting, pitch attitude, or flight configuration (fig. 9-14). When airspeed changes, the pendulum has a tendency to swing away from vertical in the opposite direction of the acceleration. If the aircraft accelerates forward, the pendulum tends to swing rearward; slowing the aircraft causes the pendulum to tend to swing forward. Since the spin axis of the pendulum is perpendicular to the line of flight and the spin motor spins in the direction of flight, accelerating the spin motor causes the pendulum to swing forward, and decelerating the spin motor causes the pendulum to swing

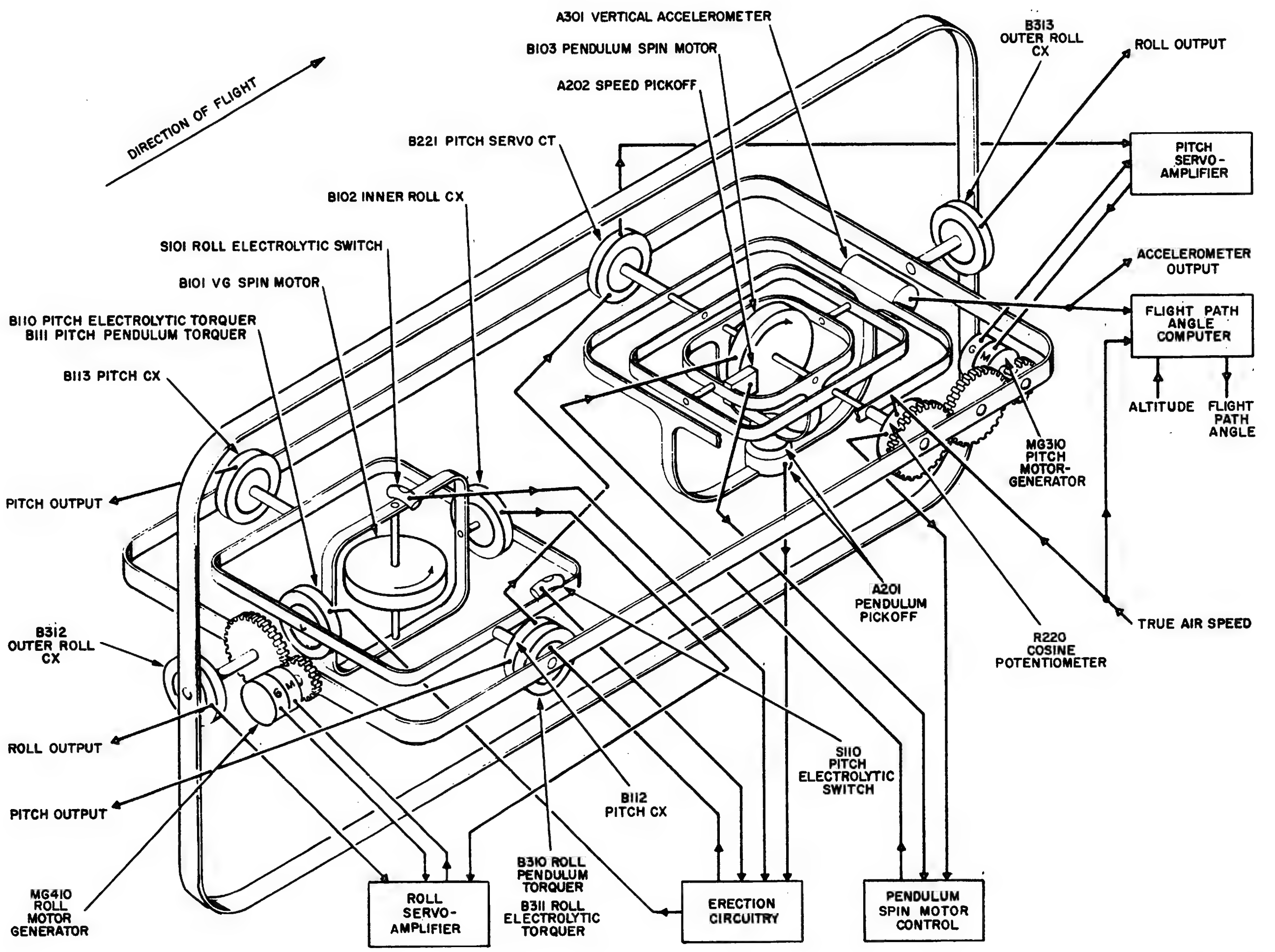

Figure 9-13.—Functional diagram of reference set.

rearward. By accelerating or decelerating the rotor proportionally to changes in airspeed, the two opposing forces can be kept equal and the pendulum maintained vertical during longitudinal accelerations of the aircraft. For example, if the airspeed increases, the tendency of the pendulum to swing rearward can be canceled by proportionally accelerating the spin motor. With sufficiently accurate sensors and proper circuit calibration, the pendulum can maintain a high degree of vertical accuracy through a wide range of acceleration.

Verticality errors which would be caused by aircraft turns are canceled by the pendulum's gyroscopic property of precession. By adjusting the spin motor speed, and thereby its angular momentum, the precession torque of the pendulum can be kept equal to the centrifugal force of the turn, and the pendulum remains vertical. If the pendulum were strictly pendulous without any gyroscopic properties, the centrifugal force of the turn would swing it outward during turns. The amount of this deviation from vertical would be determined by the pendulosity of the pendulum, the airspeed, and the turn rate. On the other hand, if the pendulum were purely gyroscopic without any pendulosity, it would be precessed about the longitudinal axis by turns about the vertical axis. The amount of this precession torque is determined by the angular momentum of the spin motor and the turn rate. Since the spin axis is perpendicular to the line of flight and the spin motor spins in the direction of flight, precession

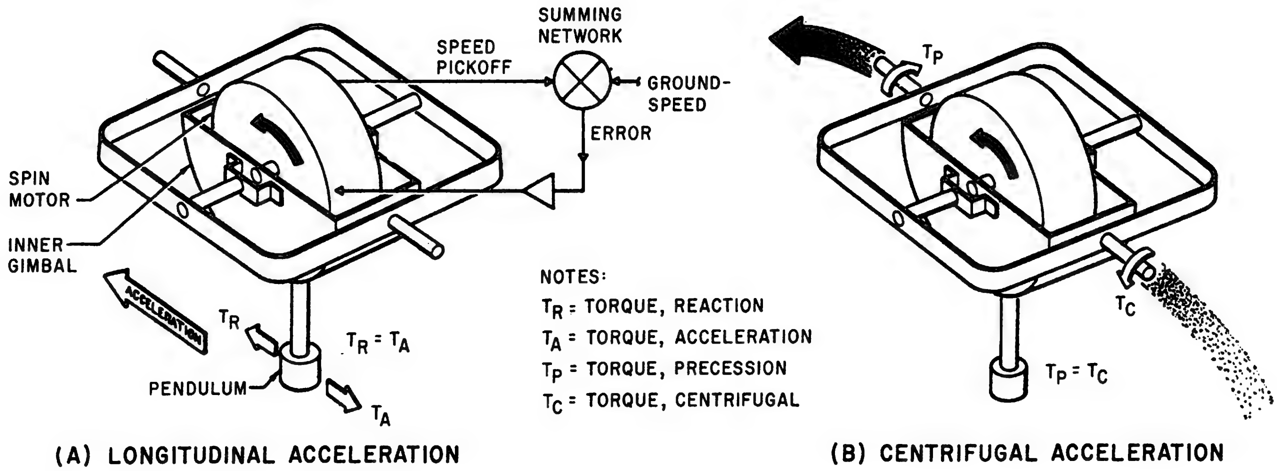

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Figure 9-14.—Geocentric pendulum. (A) Longitudinal acceleration; (B) centrifugal acceleration.

is always toward the inside of the turn. Therefore, the outward swing of the pendulum caused by the centrifugal force of a turn can be canceled by the precession torque of the pendulum when these two forces are equal. To keep these two forces equal, the speed of spin motor is kept proportional to the airspeed (the turn rate acts equally on both forces); and the pendulum remains vertical during turns.

The analytical expression for pendulum compensation of verticality errors caused by turning is

$$H\omega = PVa\omega$$

where

H = angular momentum of spin motor
ω = aircraft turn rate
P = pendulosity
Va = airspeed

As in the case of longitudinal accelerations, airspeed is the horizontal component of aircraft airspeed, so at flightpath angles other than horizontal, the horizontal component must be computed.

Spin Motor Speed Control

The speed control circuit operates to keep the speed of the pendulum spin motor proportional to the horizontal component of airspeed. The two inputs to the circuit are pendulum spin motor speed and resolved airspeed. The resolved airspeed is the command signal which determines spin motor speed, while the spin motor speed input is fed back to maintain spin motor speed with a high degree of accuracy. (See fig. 9-15.)

The airspeed input signal for the reference set comes from the airspeed potentiometer in the aircraft's central air data computer. This d-c input is amplified for the speed control circuit by d-c amplifiers A21A1 and A21A2. The cosine potentiometer R220 resolves the airspeed signal into its horizontal component. It is a cosine wound resistor with its case on the outer roll gimbal and its wiper arm attached to the pendulum pitch gimbal. During horizontal flight, the output/input ratio of the cosine potentiometer is 1:1, or the output is the same as the input. As the aircraft pitch attitude deviates from horizontal, the output of the cosine potentiometer decreases by the cosine of the pitch angle. This horizontal component of airspeed is applied through the speed control calibration adjustment resistor A14R12 to the modulator A20. In the modulator, a 400-Hz a-c signal is generated which has an amplitude proportional to the magnitude of the d-c input signal. The a-c output of the modulator is amplified through three stages of amplification—preamplifier A13, servo amplifier A19, and speed control output amplifier A11—before being applied to the pendulum spin motor control winding. The pendulum spin motor is a 2-phase motor with its fixed phase winding powered by 115 volts, phase A. The speed of

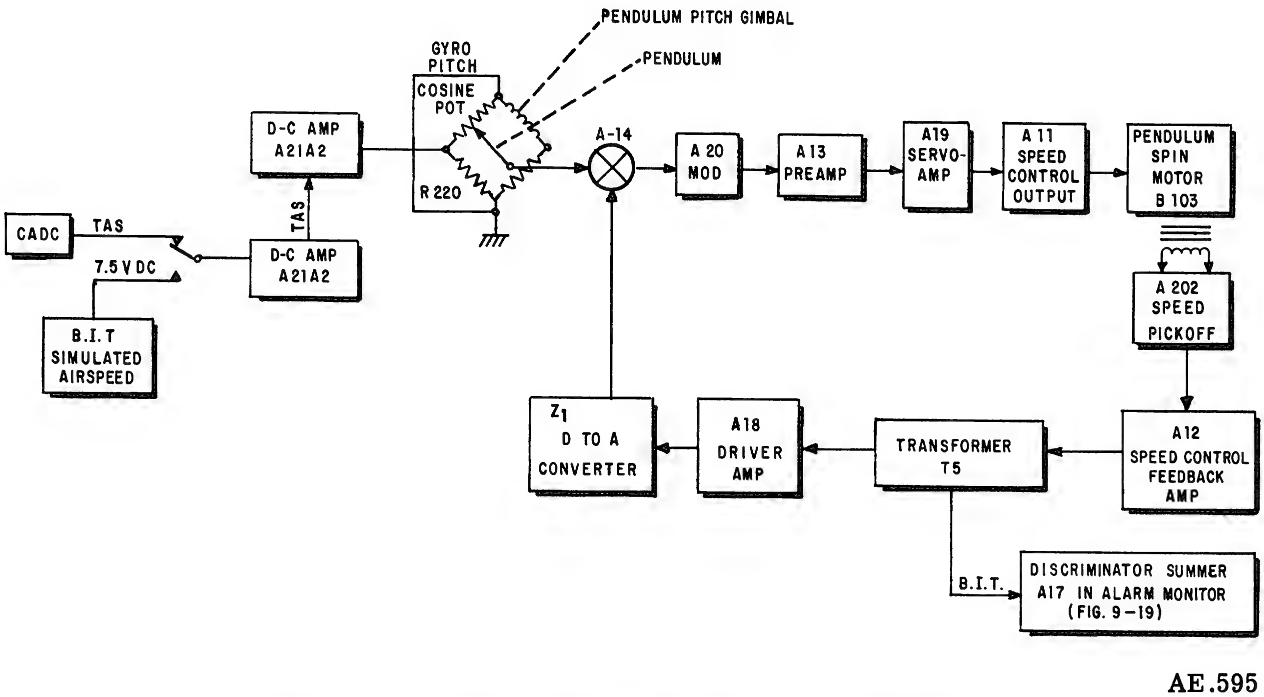

Figure 9-15.—Spin motor speed control block diagram.

the spin motor is proportional to the amplitude of the 0 to 27 volts a.c., applied to its control phase. Since the amplitude of the power applied to the control phase winding is proportional to the horizontal component of airspeed, the speed of the pendulum rotor is, in turn, proportional to the horizontal component of airspeed.

Feedback to maintain spin motor speed accurately is accomplished by a spin motor speed pickoff, conversion circuitry, and signal mixing just ahead of the modulator. The speed pickoff A202 is a winding placed close to the rim of the spin motor. As the spin motor spins, slots in its rim interrupt the induced field of the speed pickoff. These interruptions generate a pulse train in the speed pickoff. The pulse repetition rate is proportional to the speed of the spin motor. The pulses are amplified by the speed control feedback preamplifier A12. The driver A18 differentiates the pulses into positive and negative spikes. The time constant of the driver is sufficiently fast so that the highest possible pulse rate will not cause limiting of the spikes; therefore, regardless of pulse rate, all spikes contain the same amount of power. The digital to analog converter Z1 operates basically as a pulse counter, generating a d-c voltage of a magnitude directly proportional to the pulse rate. This d-c feedback signal is the opposite polarity as the airspeed d-c command signal. When the two mix at the input to the modulator A20, the resultant signal keeps the spin motor at the command speed. The speed control calibration adjustment A14R12 sets the ratio of the command signal to the feedback signal so that spin motor speed control is accurate for various combinations of attitude sensing units and computers. It is adjusted at 50 percent airspeed (750 knots) for 50 percent rotor speed (approximately 3,300 Hz).

A low speed cutoff circuit (not shown in figure 9-15) disables the speed control output amplifier, A11, below 75 knots. The d-c signal representing the horizontal component of airspeed is applied to the relay driver. Below 75 knots, 28 volts d-c, is applied to the low speed cutoff relay. When the low speed cutoff relay energizes, one set of contacts removes the 28-volt d-c B+ power from the speed control output amplifier, A11, while another set of contacts removes the power from the spin motor fixed phase winding.

Erection

The erection system operates in three modes to erect the vertical gyro in the sensor—initial erection, precise erection to pendulum vertical, and emergency operation. To meet the operating requirements of these modes, two independent erection systems are utilized—electrolytic erection and pendulum erection.

The electrolytic erection system is utilized for initial erection and emergency operation. It senses vertical with electrolytic switches and uses its own pitch and roll torquers to erect the vertical gyro. Each torquer is a 2-phase wound motor segment which uses the appropriate gimbal as its armature. Each electrolytic switch operates in a phase shifting network with two capacitors. Tilt of the gimbal unbalances the resistance of the electrolytic switch which shifts the phase of one leg of the network to lead and the other leg to lag, energizing the torquer in the appropriate direction for correction.

For initial erection, the electrolytic erection system utilizes a sequence of power application to erect the vertical gyro with a minimum of nutation during acceleration of the gyro rotor to operating speed. When the rotor has reached operating speed and the vertical gyro is erect, the electrolytic erection system is disabled and the pendulum erection system is activated.

After the initial 60 seconds, the pendulum erection system takes over erection to reference the vertical gyro to the pendulum. If in this mode the vertical gyro drifts from vertical in roll, synchro control transmitter B102 generates a comparable error signal (fig. 9-16) which is amplified by roll driver A6 and roll output amplifier A5. Motor generator MG410 is activated by the error signal and drives the outer roll gimbal so that it tracks the vertical gyro roll gimbal. Torquing of the outer roll gimbal displaces the pendulum pickoff, A20A1 and B, from null. The primary of the pendulum pickoff A201B is connected to the outer roll gimbal through the pendulum pitch gimbal, so that it is displaced from the null position (under the secondary of the pendulum pickoff A201A) when the outer roll gimbal moves. The primary is excited by phase A and a quadrature voltage, phase A - 90°. The phase A is used as the pitch erection channel reference, while the phase A - 90° voltage is the roll channel reference. The pendulum pickoff is limited to 2° of deflection from null by the pendulum housing. Error signals from the pendulum pickoff are amplified by erection amplifier A16A1 and applied to both pendulum torquers on the vertical gyro gimbals. Because the pendulum pitch torquer B111 and the pendulum roll torquer B310 on the vertical gyro gimbals are referenced the same as the pendulum pickoff, phase discrimination occurs at the torquers, and only the appropriate torquer is activated by the error signal. When the pendulum pickoff is deflected in roll, phase A - 90° error signal activates the pendulum roll torquer B310 to precess the vertical gyro roll gimbal until the vertical gyro is once again vertical with respect to the pendulum. When verticality is achieved, all error signals reduce to null.

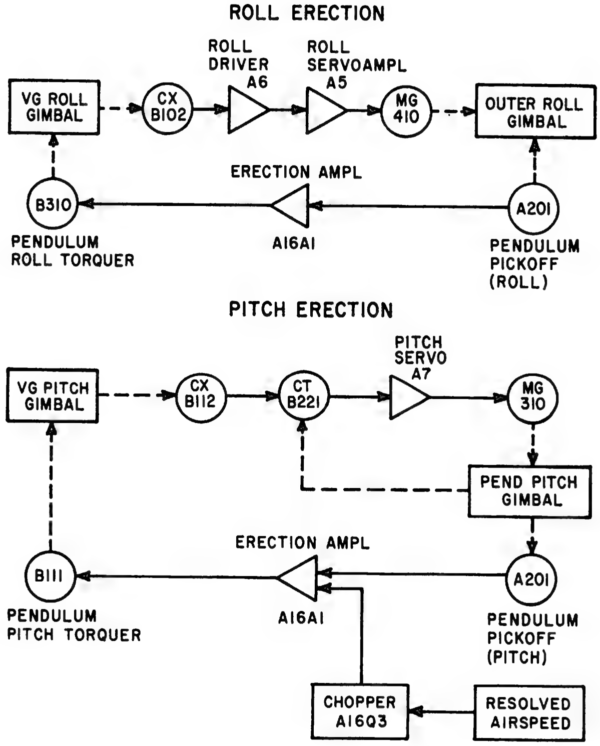

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Figure 9-16.—Pendulum erection block diagram.

If the vertical gyro drifts in pitch, synchro control transmitter B112 on the vertical gyro pitch gimbal transmits this new angle to synchro control transformer B221 on the pendulum pitch gimbal. B221 develops an error signal which activates motor generator MG310 through pitch servoamplifier A7. MG310 drives the pendulum

pitch gimbal so it tracks the vertical gyro pitch gimbal. Moving of the pendulum pitch gimbal displaces the pendulum pickoff A201 in pitch. The phase A pitch error signal generated by the displaced pendulum pickoff activates the pendulum pitch torquer B111 on the vertical gyro gimbal through the erection amplifier A16A1. The vertical gyro pitch gimbal is precessed by B111 until it erects the vertical gyro to pendulum vertical, and the error signals reduce to null. Vertical gyro verticality errors which are other than directly along the pitch or roll axes are resolved by the gimbaling into orthogonal (perpendicular) components, and proportional corrections are made by the pitch and roll erection channels

The vertical gyro is continuously corrected for earth profile errors by an airspeed input applied to the erection amplifier A16A1 (fig. 9-16). The horizontal component of airspeed is applied to chopper A16Q3 to convert its d -c magnitude into a comparable a -c amplitude. The chopper is referenced to phase A so that the earth profile correction will operate only the pendulum pitch torquer. The phase of this signal is such that the vertical gyro pitch gimbal is always driven in the dive direction, and it is attenuated to the level where the vertical gyro pitch gimbal makes just the right correction for the speed at which the aircraft is following the curvature of the earth.

The verticality error signals from the pendulum pickoff A201 are interrupted anytime the vertical gyro roll or pitch gimbals exceed an angle of 40° from their normal position. This erection cutout places the vertical gyro into free gyro operation to avoid excessive gimbaling errors which develop in the erection system at large displacement angles. The cams and switches for erection cutout are located on the vertical gyro gimbals.

In the event that the reference set should develop a malfunction, the system automatically switches to electrolytic erection. An external ON-OFF switch in the cockpit is provided to apply a ground to erection relay A1K3. This disables the pendulum erection system and reactivates the electrolytic erection system if this mode is desired. When this switching takes place, the electrolytic erection system operates on its normal erection rate of 1.5° per minute.

Roll and Pitch Signal Channels

The reference set provides two roll and two pitch output signals. (See fig. 9-17.) The roll outputs come from two synchro transmitters, B312 and B313, mounted between the ends of the outer roll gimbal and the frame of the sensor. The pitch outputs come from two synchro transmitters, B112 and B113, mounted between the vertical gyro pitch gimbal and the outer roll gimbal.

Since the outer roll gimbal is servoed to the vertical gyro roll gimbal, it accurately tracks the vertical gyro roll gimbal, and the roll output synchros are in turn referenced to the vertical gyro roll gimbal. This servo loop is interrupted during the initial 60 seconds of erection to level the outer roll gimbal to the frame and allow the vertical gyro to erect. The vertical gyro roll gimbal is referenced to the pendulum by the erection circuit described previously. An output to the alarm monitor is taken from transformer T4 to provide a warning of roll servo failure.

The pitch output synchros are referenced to the vertical gyro pitch gimbal which, in turn, is referenced to the pendulum by synchro control transformer B221 on the pendulum pitch gimbal. The pitch servo is disabled during the initial 12 seconds of the erection cycle to allow the VG motor to accelerate and the gimbals to stabilize before using the synchro control transformer B221 to provide a warning of pitch servo failure.

Flightpath Angle

Accurate flightpath angle (FPA) information is vital to some modes of operation of the aircraft. The flightpath angle is the angle of climb or dive of the aircraft velocity vector. The flightpath angle computer channel uses airspeed, barometric altitude, and vertical acceleration inputs to develop an a -c output proportional to the flightpath angle. In the computer, the airspeed along the velocity vector is compared to vertical velocity to derive flightpath angle. (See fig. 9-18.)

The analytical expression for the derivation of flightpath angle is

$$\gamma = \sin^{-1} \frac{\dot{Z}}{Va}$$

where

γ = flightpath angle

$\sin^{-1}$ = angle whose sine is

$\dot{Z}$ = vertical velocity

Va = airspeed

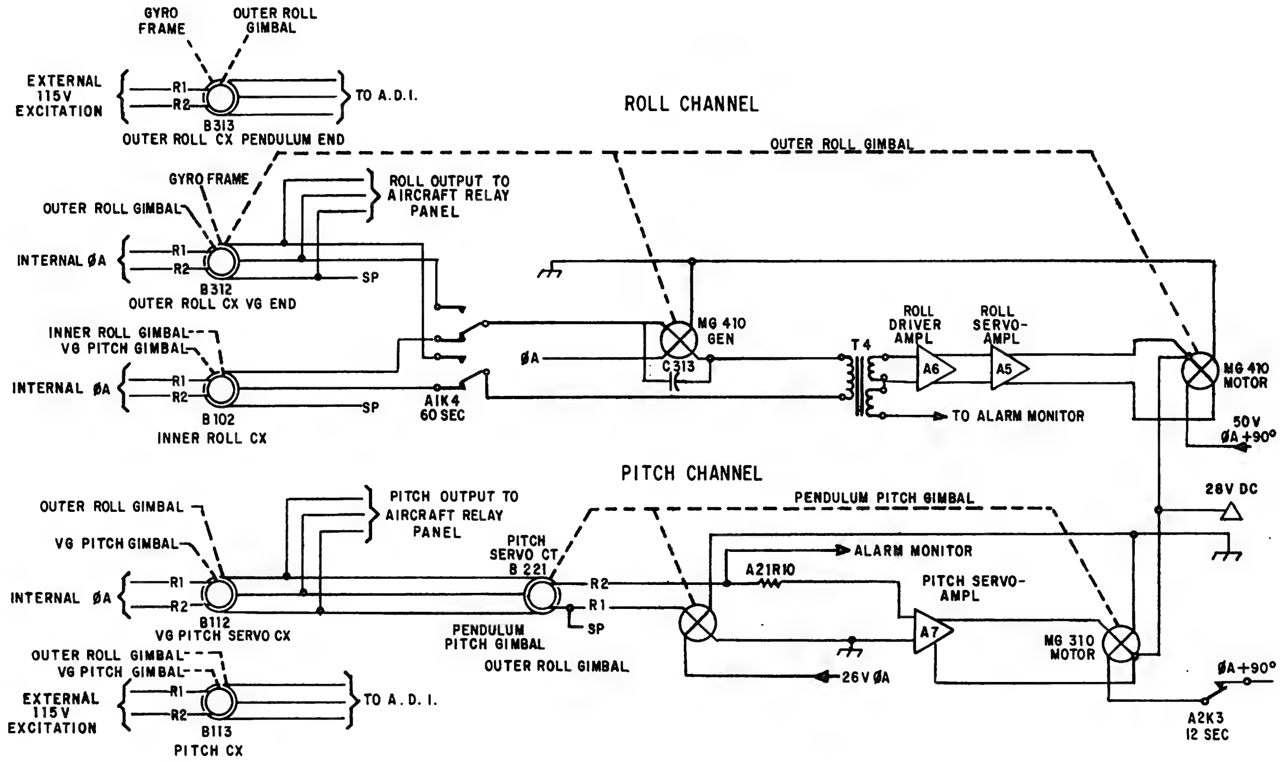

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Figure 9-17.—Pitch and roll signal flow.

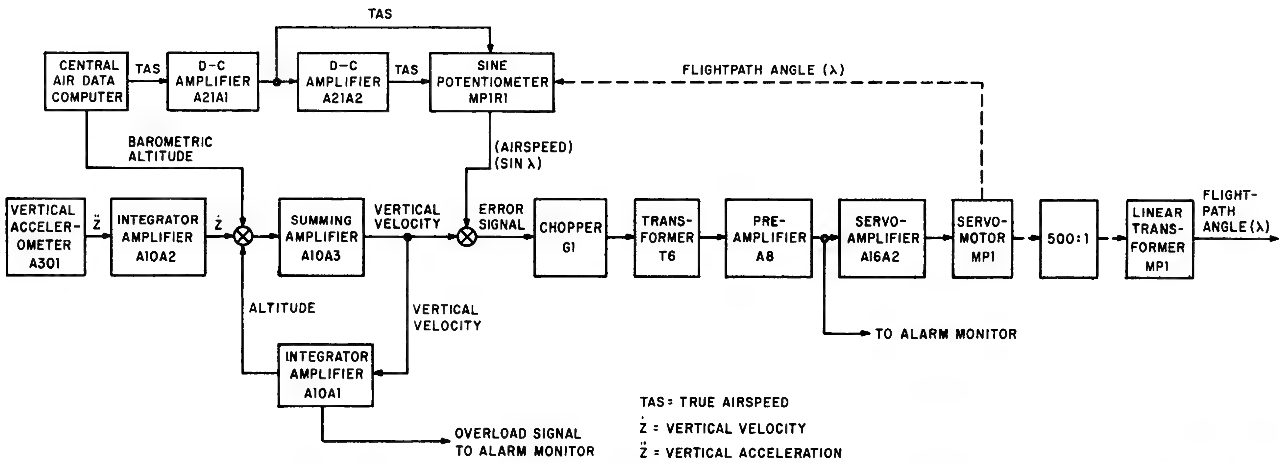

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Figure 9-18.—Flightpath angle computer block diagram.

The computer accomplishes its solution by transposing terms and solving Va sin γ = $\dot{Z}$. When airspeed times the sine of the flightpath angle equals vertical velocity, the servo loop is positioned at the flightpath angle.

A d-c airspeed signal is obtained from the airspeed potentiometer in the central air data computer. This input is amplified by d-c amplifier A21A1. Potentiometer A21R6 is a drift adjustment for the d-c amplifier. The output of the d-c amplifier is applied to one end of sine potentiometer MP1R1 and the input of d-c amplifier A21A2. D-c amplifier A21A2 reverses the polarity of its input and applies its output to the other end of the sine potentiometer. Therefore, the sine potentiometer has the opposite polarity of the airspeed signal applied to its two ends. The center of the sine potentiometer is grounded, and the wiper arm moves in a 90° arc in each direction from the grounded center tap. It is a sine wound potentiometer so that the output is the full airspeed voltage at 90° and decreases by the sine of the flightpath angle to 0 volts at 0°. The wiper arm of the sine potentiometer is driven by the flightpath angle servomotor. The d-c output from the wiper arm of the sine potentiometer is applied to chopper G1 which converts the d-c signal to a-c for use by the flightpath angle servo.

The vertical accelerometer is utilized for the determination of the vertical velocity signal. Vertical acceleration is applied to integrator amplifier A10A2 through a voltage divider network (A10R15, A10R16, and A10R17). The output of A10A2 is vertical velocity which is then scaled and fed to summing amplifier A10A3. The output of A10A3 is utilized in the computation of flightpath angle.

Barometric altitude is used in the vertical velocity circuit for long term stabilization during constant vertical velocity conditions as follows: The output of summing amplifier A10A3 is fed to integrator amplifier A10A1 which produces computed altitude. This signal is then compared with barometric altitude signal at pin 2 of amplifier A10A3. The difference between these signals is then used to correct the vertical velocity output of A10A3.

The computed vertical component of airspeed signal from the sine potentiometer and the vertical velocity signal from summing amplifier A10A3 are compared at chopper G1. These two signals are connected series opposing so that current flows in the primary of transformer T6 only when there is a difference in their values. Semiconductors A10CR2 and A10CR3 provide arc suppression for the chopper contacts. Inequality of the two signals develops an a-c error signal in the secondary of T6, which is applied to the gain control circuit for limiting of amplitude changes. Preamplifier A8 and servoamplifier A16A2 provide power to the flightpath angle motor which drives the sine potentiometer until its output equals the output from the summing amplifier. At this time, the sine potentiometer is positioned at the flightpath angle. Since the linear transformer is also driven by the flightpath angle motor it develops an a-c output whose amplitude and phase are indicative of the flightpath angle.

Alarm Monitor

The alarm monitor (fig. 9-19) provides warning in the event of a failure which would produce unreliable indications from the vertical reference set. It monitors 3-phase a-c power, 28-volt d-c power, positive and negative 28-volt derived d.c., positive and negative 15-volt regulated d c, pitch servo channel, roll servo channel, and flightpath angle computer. If any of these functions fail, the alarm monitor will cause warning flags in the indicator to appear, the PRIM GYRO OFF light to light, and the system will automatically switch to electrolytic erection.

In normal operation the alarm monitor circuit holds relay A2K1 energized. Relay A2K1 in turn holds relay A2K4 energized. These two relays control power OFF and displacement warning flags in the attitude indicator and the PRIM GYRO OFF light on the right-hand console caution lights panel, and the erection relay A1K3. If there is a failure in the reference set, the alarm monitor allows these two relays to deenergize which causes the flags to appear in the attitude indicator, the warning light will come on, and the system will revert to electrolytic erection.

The alarm monitor monitors the neutral leg of the 3-phase power applied to the vertical gyro rotor B101. If any leg of the 3-phase power fails, current flows in the netural line. This current flow is sensed by the alarm monitor which operates the warning flags and light.

In the event of failure of the aircraft 28-volts d-c, the power relay, K3, will deenergize, interrupting the 3-phase a-c power. Interruption of the a-c power will cause failure of the positive and negative regulated 28 volts d-c and the positive and negative regulated 15 volts d-c The regulated 28 volts d-c is monitored by the 28-volt d-c monitor A17. If the positive regulated 28 volts d-c drops

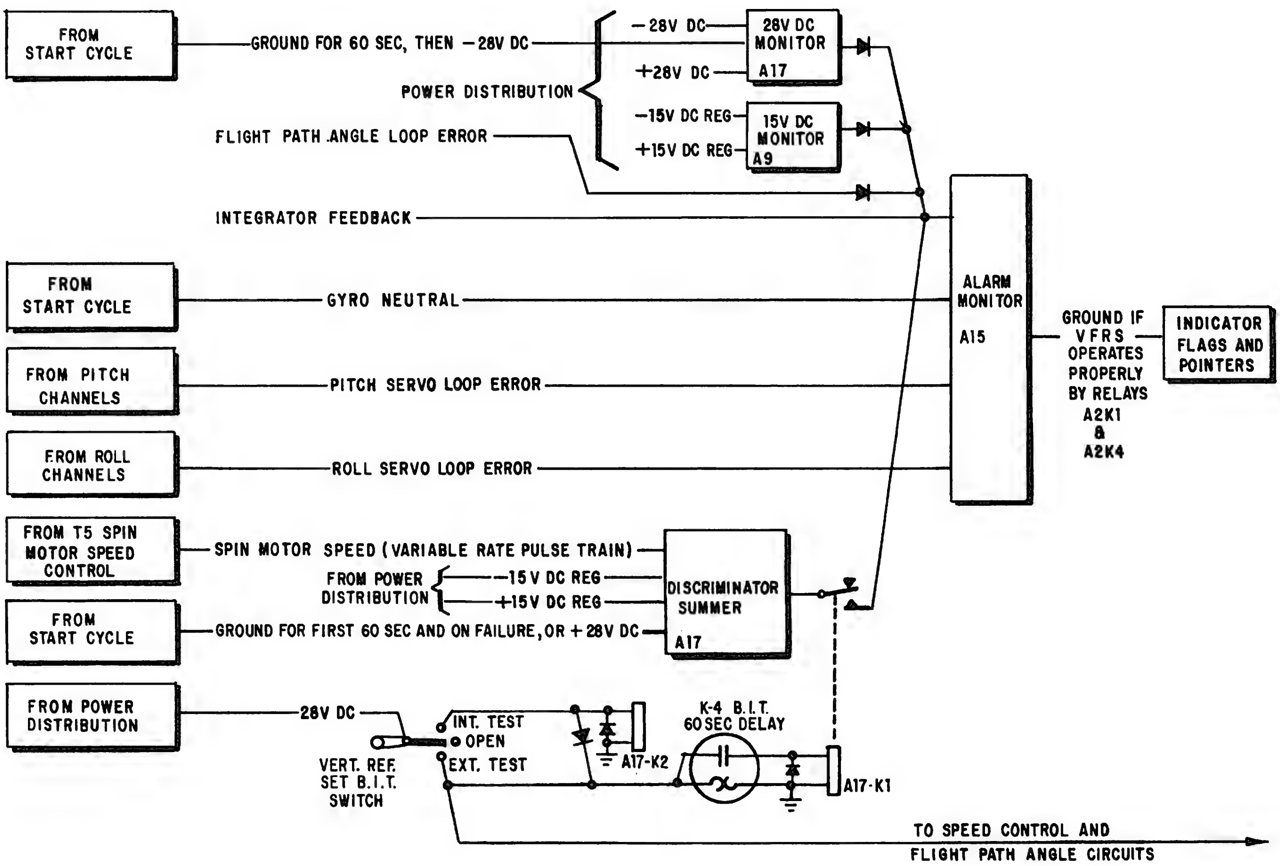

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Figure 9-19.—Alarm monitor block diagram.

below 15 volts or the negative regulated 28 volts d.c. drops below 22 volts, the alarm monitor operates. The positive and negative regulated 15 volts d.c. is monitored by the 15-volt d -c monitor A9. If the regulated 15 volts d.c. drops below 9 volts, the alarm monitor operates. For the initial 60 seconds of operation of the reference set, the negative regulated 28 volts d.c. is returned to ground through resistors A9R4, A9R5, A9R6 (located in the 28-volt d -c monitor A17), and the contacts of the 60-second thermal start cycle relay, K1. The alarm monitor sees this condition as a failure of the negative 28 volts d.c. and keeps the warning flags in view for the initial 60 seconds.

The pitch signal channel is monitored at the pitch servo CT, B221. If the pitch channel malfunctions, the error signal in B221 will become excessive. The alarm monitor operates when the error builds up to 10°. The roll signal channel is monitored in a similar manner at transformer T4. The alarm monitor operates when the roll error reaches 3°.

Flightpath angle computer failures are detected at either of two points—at feedback integrator A10A1 or at preamplifier A8. If the vertical velocity computer malfunctions, the feedback integrator A10A1 will draw excessive current, causing the alarm monitor to operate. Excessive servo loop errors will cause excessive output from the preamplifier A8. This condition also causes the alarm monitor to operate.

Built-In Test Circuit

The built-in-test (BIT) circuit works through the alarm monitor (fig. 9-19) to indicate whether the pendulum spin motor speed control circuits

are operating correctly (fig. 9-15). If the speed control is not operating correctly, the alarm monitor will cause the warning flags and light to indicate failure when the BIT check is performed. If the speed control is operating correctly when the BIT check is performed, the warning flags will wave and the light will flash on and off at a steady rate.

When the cockpit mounted BIT switch is placed in INTERNAL position, relay A17K2 is energized and thermal relay K4 begins to heat. Relay A17K2 substitutes the 7.5-volt d.c. signal for the airspeed input signal to the speed control circuit. This simulated airspeed signal will drive the pendulum spin motor at 50 percent speed (half speed produces approximately 3,300 pulses per second). Thermal relay K4 has a 60-second delay to allow the circuits to stabilize prior to testing. At 60 seconds, the contacts of K4 close and relay A17K1 is energized connecting the BIT circuit to the alarm monitor. Pendulum spin motor speed is monitored by the BIT circuits at transformer T5. This variable rate pulse train is monitored by the BIT discriminator summer circuitry A17. This is accomplished by network A17CR3, A17C2, and A17R4, and network A17CR5, A17C3, and A17R10. BIT sense level potentiometer A17R4 adjusts the high speed limit of the BIT circuit. BIT sense level potentiometer A17R10 adjusts the low speed limit. If the spin motor speed is too high, semiconductor A17CR4 conducts and develops an output for the alarm monitor. If the spin motor speed is too low, semiconductor A17CR6 conducts to develop the output. When the spin motor speed is within the specified limits, there is no output from the BIT discriminator summer. With no output from the discriminator summer, capacitor A17C1 charges from the positive 28 volt d -c supply through A17R1 and A1K3 until A17CR2 conducts and the alarm monitor deenergizes relay A2K1. When relay A2K1 deenergizes, it provides a discharge path for capacitor A17C1 through A17R2 by grounding A17R1. Capacitor A17C1 discharges until it reaches a level which permits the alarm monitor to reenergize relay A2K1. This circuit continues to cycle, waving the flags and flashing the warning light to indicate that the pendulum spin motor speed control is operating correctly. If the spin motor is operating too fast or too slow, the output of the BIT discriminator summer causes the alarm monitor to keep relay A2K1 deenergized, the flags in view, and the warning light lit.

The BIT check is the only test performed on the VFRS at the organizational level maintenance. If the VFRS fails the BIT check, the reference set, sensor, and computer must be removed as a unit for repair and calibration at the intermediate level maintenance.

The "EXTERNAL" position on the BIT switch is used for applying an external signal for calibration purposes, which is also performed at the intermediate, or higher, level maintenance.

Power Distribution

The reference set uses 115-volt, 400-Hz, 3-phase wye-connected a -c power and 28-volt d -c power. This power enters the computer through the contacts of power relay K3. Aircraft supplied 28 volts d.c. holds K3 energized when ground is applied to the relay from an external ON-OFF control circuit.

The computer derives positive and negative 28 volts d.c. and positive and negative regulated 15 volts d.c. from the 3-phase a -c aircraft power. These regulated voltages are used in circuits where power variations would degrade performance. The unregulated 28-volt d -c aircraft power is used primarily where considerable current is required, such as for energizing relays and for amplifier output stages.

When power is initially applied to the reference set, the 12-second thermal delay relay K2 is activated by 115 volts, phase C, and the 60-second thermal delay relay K1 is activated by 115 volts, phase B. As the normally closed contacts of these relays open, relays in the erection circuit are operated to produce the results described earlier. Power for the erection circuits is provided by transformer T1 from 115 volts, phase A.

SUMMARY OF VFRS OPERATION

Figure 9-20 provides a simplified functional block diagram of the VFRS. The functions of the major circuits—outlined by a single line—are as follows:

1. The power distribution circuits receive aircraft power, modify power to system requirements, and distribute power to the system.
2. The start cycle relay circuits control power application to the vertical gyro and to the gyro erection circuits to insure proper erection.
3. The electrolytic-controlled erection circuits initially erect the gyro to a spin-axis vertical position.

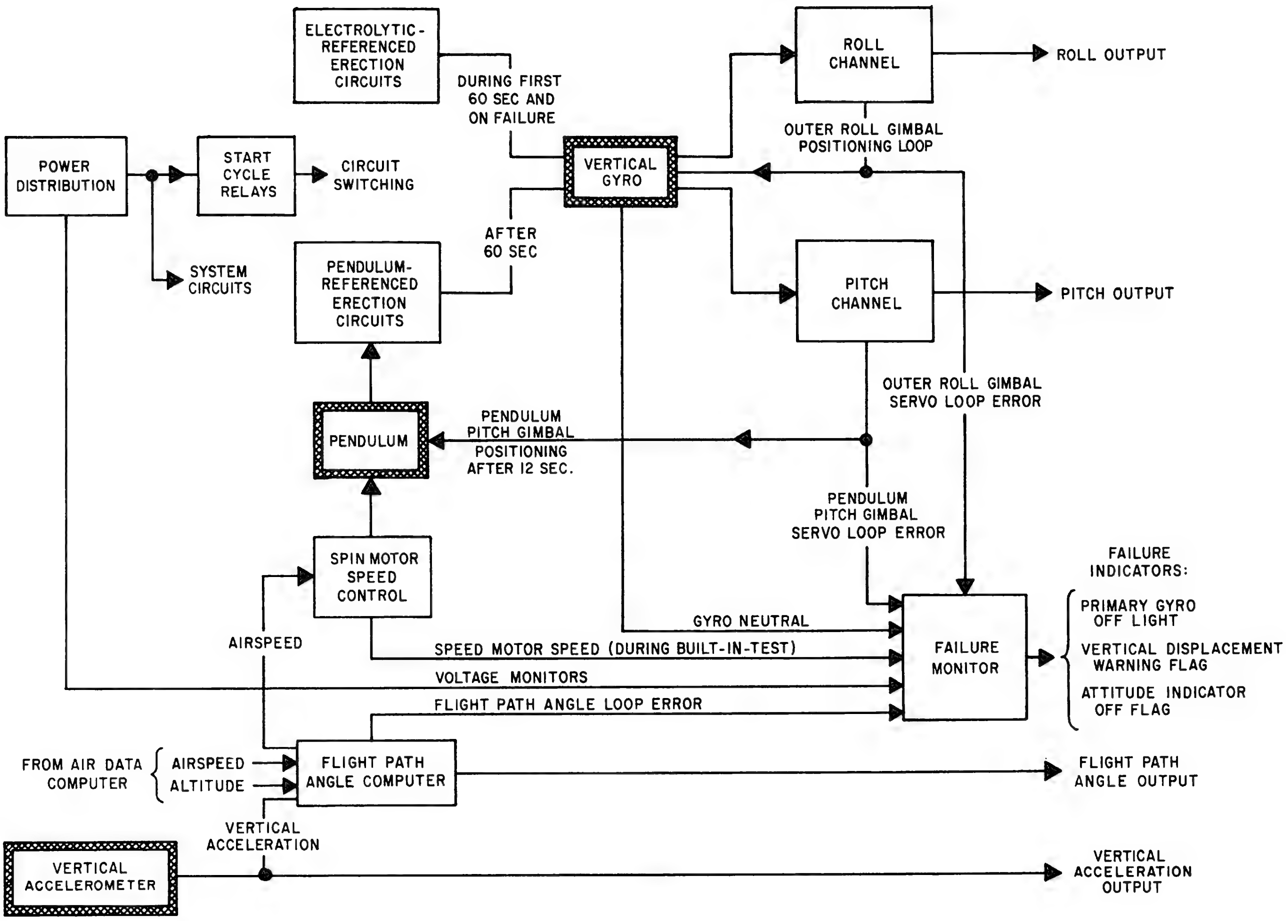

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Figure 9-20.—VFRS block diagram.

4. The roll channel provides the system roll output signal, and incorporates a servo loop to position the outer roll gimbal.

5. The pitch channel provides the system pitch output signal, and incorporates a servo loop to position the pendulum pitch gimbal.

6. The pendulum-referenced erection circuits assume control of gyro erection approximately 60 seconds after power application to the system, and maintain the spin axis vertical.

7. The spin motor speed control circuits control pendulum spin motor speed to counteract the effects of acceleration on the pendulum.

8. The flightpath angle computer circuits receive airspeed, altitude, and vertical acceleration signals and compute the flightpath angle. Airspeed is also applied to the spin motor speed control circuits.

9. The failure monitor monitors various parameters throughout the system and activates indicators in the event of failure.

CHAPTER 10

AUTOMATIC FLIGHT CONTROL SYSTEM

The first electronic automatic flight control system (AFCS) to be installed in naval aircraft was the Eclipse-Pioneer P-1 automatic pilot. The P-1 is a closely integrated system which was ideally suited to the requirements of the then current aircraft. It served the dual purpose of providing direction and attitude indications to the pilot as well as stabilization signals for autopilot control.

While highly satisfactory operation was obtained in the earlier aircraft, tests indicated that the system did not provide adequate control, nor did it provide all of the desirable features needed for later aircraft. Hence, development of the Eclipse-Pioneer P-3, the General Electric G-3, and the Sperry S-5 was undertaken.

It is suggested that the AE familiarize himself with the information contained in chapter 21 of AE 3 & 2, NavPers 10348-C. This chapter discusses the theory and operation of the P-1 automatic pilot. The operation of this automatic pilot is entirely electrical and provides magnetic heading control, automatic synchronization, and maneuvering control. To these features the P-3, G-3, and S-5 autopilots added barometric altitude control, increased the maneuvering limits, and included three-axis rate damping. They also provided improved servo response and increased vertical gyro accuracy.

During the period of transition from the P-1 autopilot to the P-3, G-3, and S-5, considerable changes developed in naval aircraft. The jet engine produced greater speed ranges and higher control forces, which required the installation of boost or full power surface control systems. Also, many aerodynamic and control system changes were made to obtain the specified performance characteristics. In many cases these changes necessitated corresponding changes in automatic flight control systems (AFCS).

It is beyond the scope of this training manual to discuss all types of automatic flight control systems. However, with a knowledge of the basic functions of the autopilot and some of the newer developments, this chapter will familiarize the AE with the operation and function of the newer types. A typical system, the AN/ASW-16 which is used in the A-6A aircraft, has been selected for discussion in this course. To provide the AE with an understanding of the overall operation and the relationship of the AFCS and other aircraft systems, the modes of operation are discussed first; and second a functional description of the system components is given. The remaining portion of the chapter is devoted to a discussion of the theory of operation.

MODES OF OPERATION

The Automatic Flight Control System AN/ASW-16 is an electromechanical error-sensing, coupling, shaping, and amplifying system. In general, it consists of three main control loops that correspond to the aircraft control axes—rudder (yaw), flaperon (roll), and stabilizer (pitch). The system provides three-axis stability augmentation, attitude control, and automatic flightpath control of the aircraft. The system can be operated in any one of the following seven modes:

1. Stability augmentation.
2. Attitude hold.
3. Altitude hold.
4. Mach hold.
5. Return to level.
6. TPQ-10-(radio receiver ground control steering).
7. Command—(including roll- and g-commands from the ballistic computer set or automatic landing system (ALS) data link inputs).

Each of these modes is manually selectable by the pilot if the AFCS interlocks are satisfied.

The ALS data link, TPQ-10, and command modes are not presently implemented in the aircraft. However, the system does contain the necessary circuitry to be used with ALS equipment when it is installed. The overall relationship between the AFCS and the other aircraft systems is illustrated in figure 10-1. A brief discussion of each of the operating modes is presented in the following paragraphs.

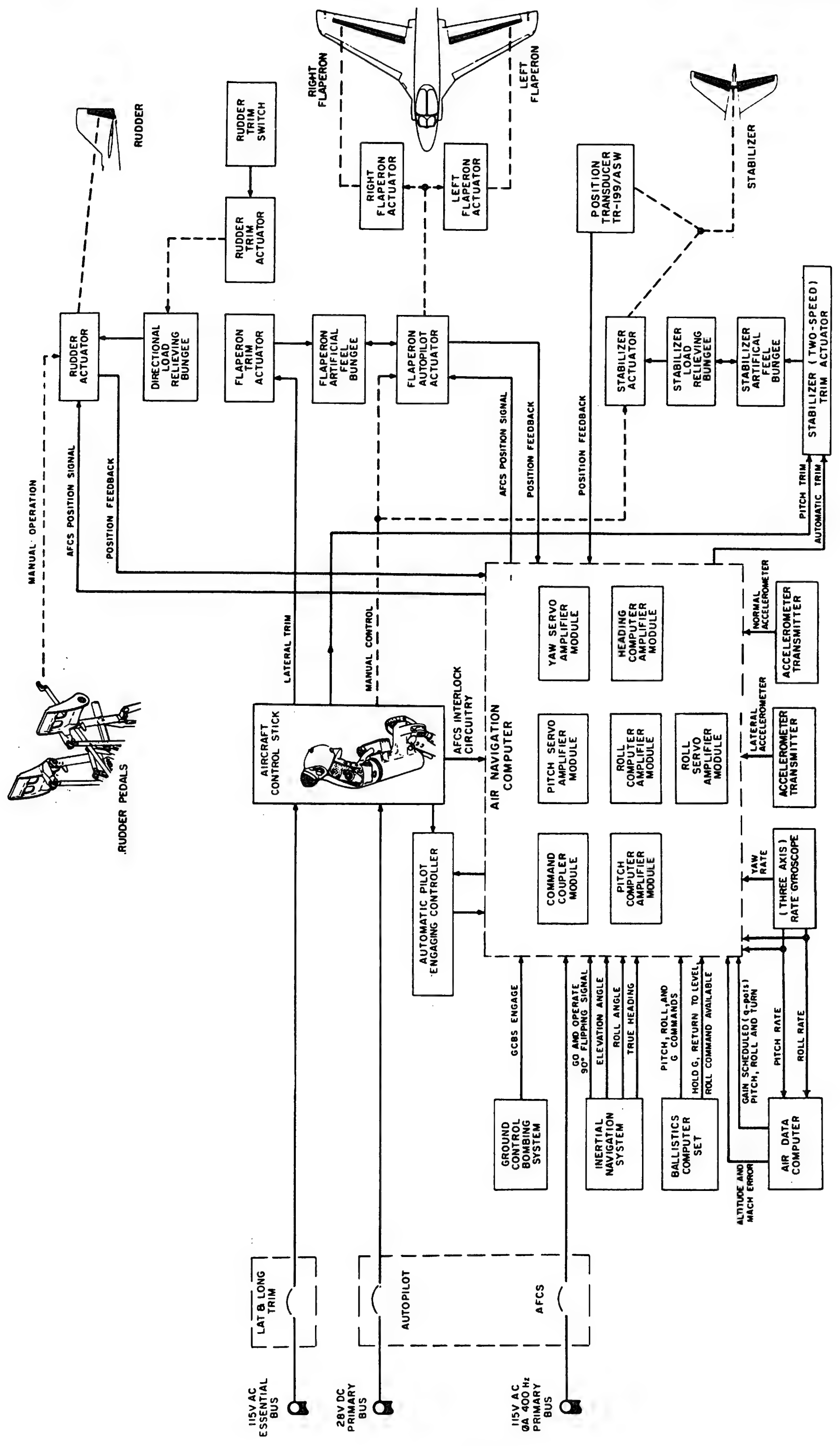

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Figure 10-1.—AFCS AN/ASW-16 block diagram.

STABILITY AUGMENTATION MODE

The stability augmentation mode performs four specific functions—pitch, roll, and yaw damping, and turn coordination. The three-axis damper automatically reduces aircraft motion in each axis by positioning the stabilizer, flaperon, and rudder in proportion to aircraft pitch rate, roll rate, and yaw rate, respectively. Signals from rate gyroscopes are used to command control surface positions through electrohydraulic actuators. Turn coordination provides automatic coordinated turns. Stability augmentation also positions the rudder, through the rudder actuator in response to aircraft side acceleration.

ATTITUDE HOLD MODE

The attitude hold mode is the basic, hands-off mode of operation. While operating in this mode, the pilot may, if he desires, initiate roll and pitch maneuvers using the aircraft control stick. (This operation is actually a submode of operation within the major mode and is described later.) Three-axis damping is also provided while operating in the attitude hold mode.

The rudder (yaw) axis is controlled in this mode in the same manner as it is in the stability augmentation mode.

The stabilizer (pitch) axis maintains the reference pitch attitude and furnishes continuous automatic pitch trim. Pitch automatic hold is accomplished by commanding stabilizer position proportional to pitch attitude rate and displacement from an established reference attitude. The rate signal is derived from a pitch rate gyro and the displacement signal is received from the inertial navigation system (INS). These signals position the stabilizer through the stabilizer electrohydraulic actuator. Automatic pitch trim is accomplished by repositioning the cockpit control column and linkage to establish the trimmed stabilizer position. The AFCS senses sustained electrically held surface position and repositions the control column and linkage through the electromechanical trim actuator, thereby eliminating the requirement for sustained electrical input.

In the operation of the flaperon (roll) axis, there are two possible configurations under the control of the AFCS—roll attitude hold and heading hold. Roll attitude hold is accomplished in the same way as pitch attitude hold, with the flaperon being positioned as a function of roll rate gyro and INS roll attitude error information. In order for the AFCS to assume the roll attitude hold configuration, the aircraft bank angle must be greater than 5° when the attitude hold mode is selected. If the bank angle is less than 5° when this mode is selected, the aircraft is automatically leveled and the heading hold mode is engaged. The reference heading is maintained by commanding bank angle as a function of heading error. The heading error signal is also derived from the aircraft's inertial navigation system. The actuator positions the flaperon through linkage and through the flaperon power actuators.

With the AFCS in the attitude hold mode, the pilot can initiate roll and pitch maneuvers using the aircraft control stick. Force-sensitive disconnect switches within the control stick cause the AFCS to revert to the stability augmentation mode when control stick force is applied. The attitude hold mode is automatically reengaged when the aircraft maneuver is completed.

When the stick is moved laterally out-of-detent, the roll damper signal is removed from the AFCS. The roll rate signals are removed by an easy engage circuit within the AFCS for the duration of the laterally applied force. Removal of the roll damper signal eliminates damper resistance to the command roll rate. When the stick is returned to lateral detent, the roll damper signal is reapplied smoothly to the desired level through the AFCS easy engage circuit.

ALTITUDE HOLD MODE

Automatic barometric altitude hold is accomplished by commanding pitch attitude proportional to displacement and rate deviations from the reference altitude. In addition, sustained altitude errors are corrected by integration of the displacement error. The displacement signal (derived from a clutched synchro in the aircraft air data computer), the rate signal (derived through integration of the accelerometer transmitter signal—normal acceleration), and the integrated displacement signal are summed and used to command aircraft pitch attitude in the sense that reduces the altitude error. The stabilizer is positioned by the electrohydraulic stabliizer actuator. At altitudes below 5,000 feet, the barometric

altitude error signal is modified in the aircraft's air data computer by a radar altimeter altitude signal to correct for altitude hold deviations caused by ambient barometric pressure changes.

MACH HOLD MODE

Mach hold is accomplished by commanding aircraft pitch attitude that reduces Mach error in the same manner as altitude error is reduced in the altitude hold mode. The displacement signal is derived from a clutched reference synchro in the air data computer. Sustained Mach errors are corrected by integration of the displacement error, and vertical path damping is provided through integration of the normal accelerometer transmitter signal.

RETURN-TO-LEVEL MODE

The return-to-level mode is manually selected by the pilot (or is automatically commanded by the ballistic computer in the command mode) in any attitude, provided the system interlock functions are satisfied. Manual selection of this mode of control results in the following programmed sequence:

1. Disconnect roll attitude hold, and level the aircraft in roll.
2. Engage heading hold when the bank angle is reduced to 5°.
3. Disconnect pitch attitude, altitude, or Mach hold, and level the aircraft in pitch.
4. Engage pitch attitude hold when pitch angle is reduced from 3° to 7°.

TPQ-10 MODE

This mode of operation is manually selected by means of the TPQ-10 engage switch on the ground controlled bombing system (GCBS) control panel. Steering command signals are generated by the heading computer module of the air navigation computer in response to signals transmitted from the ground data link transmitter to the aircraft radio receiver. The resulting heading error signal is reduced to zero by commanding bank angle as a function of heading error (as in heading hold), thus changing the aircraft heading in response to ground commands.

COMMAND MODE

In the command mode of operation, fully automatic hands-off control of the aircraft is achieved by the AFCS in response to programed ballistic computer set inputs. The ballistic computer provides steering error inputs in the form of roll commands (limited to ±30°), velocity inputs, and normal-acceleration-monitored g-command inputs. (Lateral axis commands may be inserted with the pitch axis in the attitude, altitude, or Mach hold configuration.) Closed loop g-control is achieved in the AFCS by comparing the g-command signal with the normal acceleration measured by the accelerometer transmitter reference. This error signal is integrated and used to command stabilizer position. In the command mode, the AFCS has the additional capability of accepting roll and pitch commands from an airborne data link for automatic landing system (ALS) operation.

FUNCTIONAL OPERATION OF SYSTEM COMPONENTS

The automatic flight control system consists of the air navigation computer, an automatic pilot engaging controller, rate gyros, a positioning transducer, the aircraft control stick and control surface actuators. Although the navigation computer is the major system component, it is described last since inputs to the computer come from many of the other system components. By giving a description of the other components first, it should be easier to understand the operation of the computer.

ACTUATORS

The actuators in the system can be divided into three groups—stabilizer actuator group, flaperon actuator group (consisting of flaperon actuator and flaperon autopilot actuator), and rudder actuator group. Except for the autopilot actuator, each of the actuators is a tandem arrangement of two double-acting power pistons mounted on a common rod. Each of the actuators is discussed under the appropriate heading.

Stabilizer Actuator

The stabilizer actuator (fig. 10-2) controls the movement of the stabilizer in response to mechanical commands from the pilot and to electrical commands from the AFCS. A valve

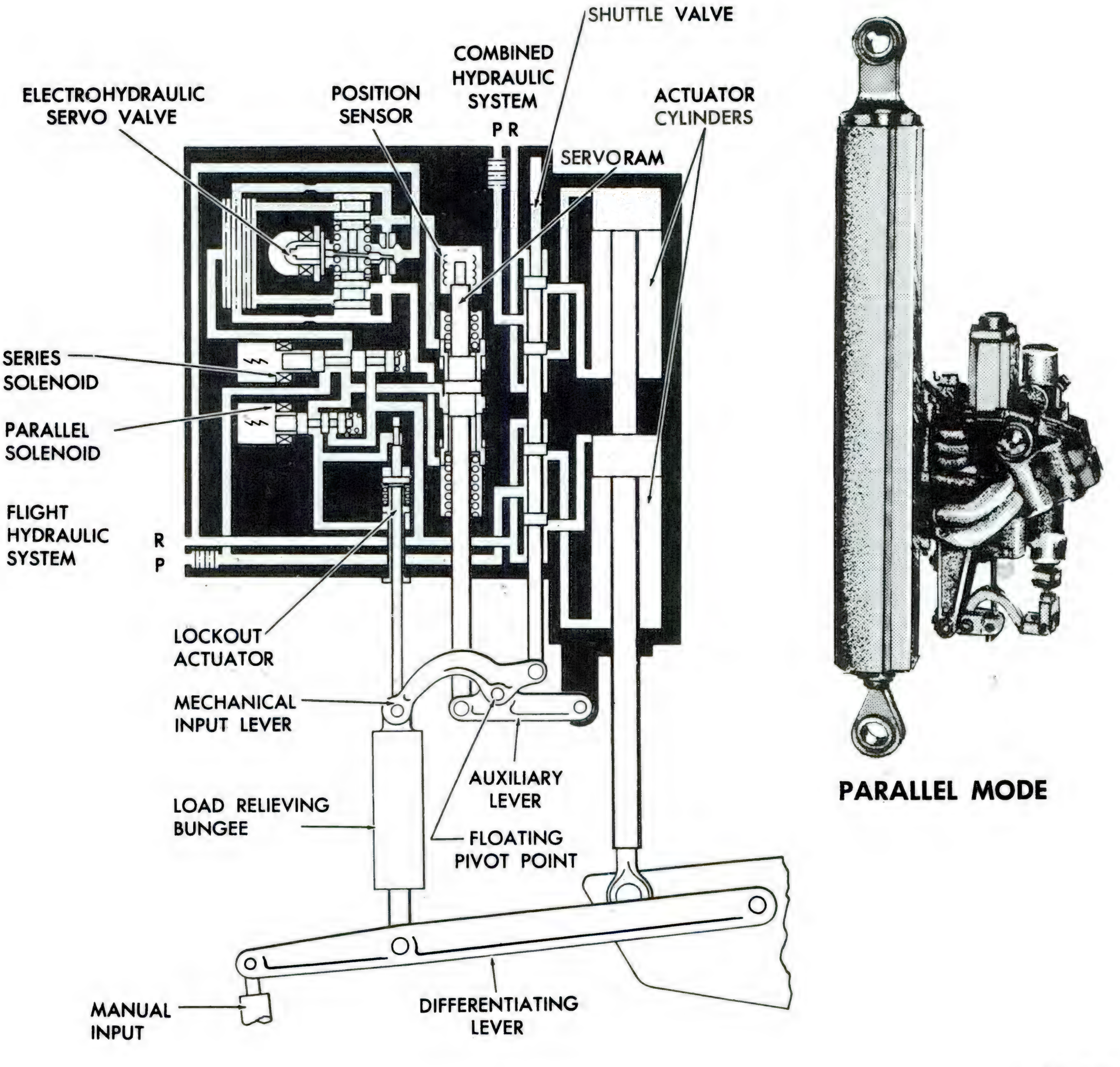

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Figure 10-2.—Stabilizer actuator.

section on the cylinder housing contains two tandem power valves (shuttle valves) that meter flow from two separate hydraulic systems to the cylinders. The valve section includes the power (shuttle) valves, electrohydraulic servo valve, series (mode) and parallel (mode) solenoid valves, servo ram, auxiliary lever, and mechanical input lockout pistons. This actuator operates in three modes—manual, series, and parallel.

In the manual mode, the pilot's movement of the control stick controls the power valve, which ports hydraulic fluid to the actuator cylinders.

When the stabilizer actuator operates in the series mode, the series solenoid valve is

controlled from the automatic pilot engaging controller. In the series mode of operation, input signals from the AFCS may be used independently or summed with the control stick movement to position the stabilizer.

When the stabilizer actuator operates in the parallel mode, both the series and parallel mode valves are energized. As in the series mode, electrical signals from the AFCS operate the electrohydraulic servo valve, which drives the shuttle through the servo ram, auxiliary lever, and mechanical input lever. Inner loop feedback is again accomplished by the position sensor on the servo-ram shaft. Since the mechanical input point is locked, stabilizer movement produces no mechanical feedback to the valve. The outer loop feedback is accomplished electrically by means of the position sensor. This unit is mechanically linked to the stabilizer actuating arm to sense motion of the stabilizer. During manual and series operation, an electric clutch disengages the position sensor and centering springs hold its rotor in the null position. When the valve input point is fixed, motion of the stabilizer actuating arm drives the control linkage, and the pilot's control stick follows surface position. Full surface authority is available in this mode of operation.

STABILIZER TRIM ACTUATOR.—Two modes of trim actuator operation are provided—a high speed manual mode and low speed AFCS mode. The two-speed actuator (fig. 10-3) consists of two 120-volt, 400-Hz, single-phase motors, a motor brake, gearbox, and screwjack. A ball-detent slip clutch is also included to prevent excessive actuator loading.

High speed operation of the actuator is controlled by the manual trim button located on the aircraft control stick. Low speed operation is controlled by the automatic pitch trim circuitry of the AFCS. The motor and gearing associated with the automatic circuitry drive the actuator at a trim rate that is approximately one-twentieth the manual rate. The slower rate for automatic trimming is required for stable system operation.

The actuator output moves the control stick through an artificial feel bungee. Adjustable stops incorporated in the screwjack sleeve of the actuator provide mechanical adjustment.

The brake assembly, which is an integral part of each motor, is released upon application of power to the motor.

POSITION TRANSDUCER.—The position transducer (fig. 10-4) is a linear transducer

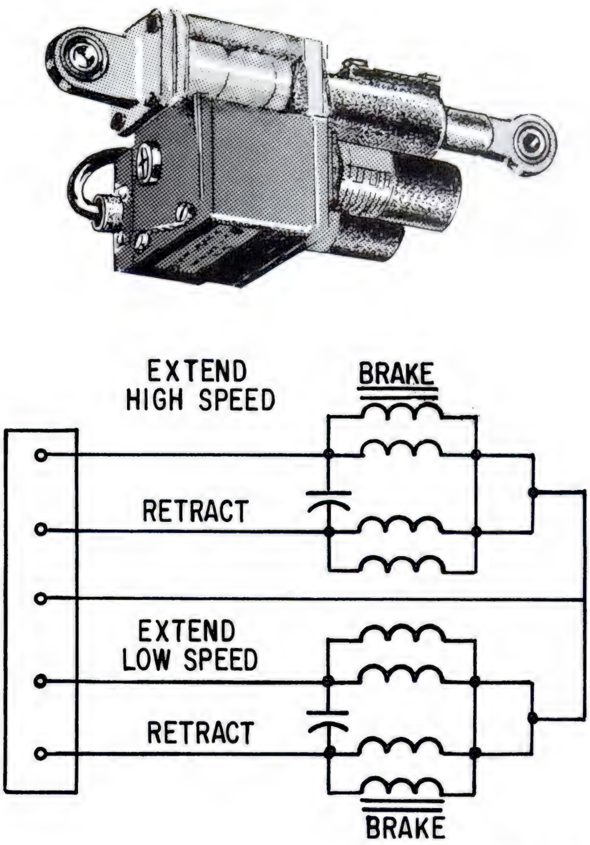

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Figure 10-3.—Trim actuator.

that transmits stabilizer position to the AFCS when the stabilizer actuator is operating in the parallel mode. The transducer contains a linear transformer, a mechanical recentering device, an electromechanical clutch, a gear train, and an input shaft. The transducer input shaft is mechanically linked through adjustable linkage to the stabilizer.

Input shaft rotation is transmitted through a clutched gear train to the rotor windings of the linear transformer. The d-c operated clutch and the parallel solenoid of the stabilizer actuator are simultaneously energized through the AFCS interlock circuitry. The rotor excitation voltage (26 volts a.c.) is center-tapped from the air navigation computer. Rotation of the transformer rotor induces a signal in the stator windings that is proportional to stabilizer position. The stator output signal is fed back to the stabilizer AFCS servo loop. A centering spring within the transducer returns the rotor to the electrical

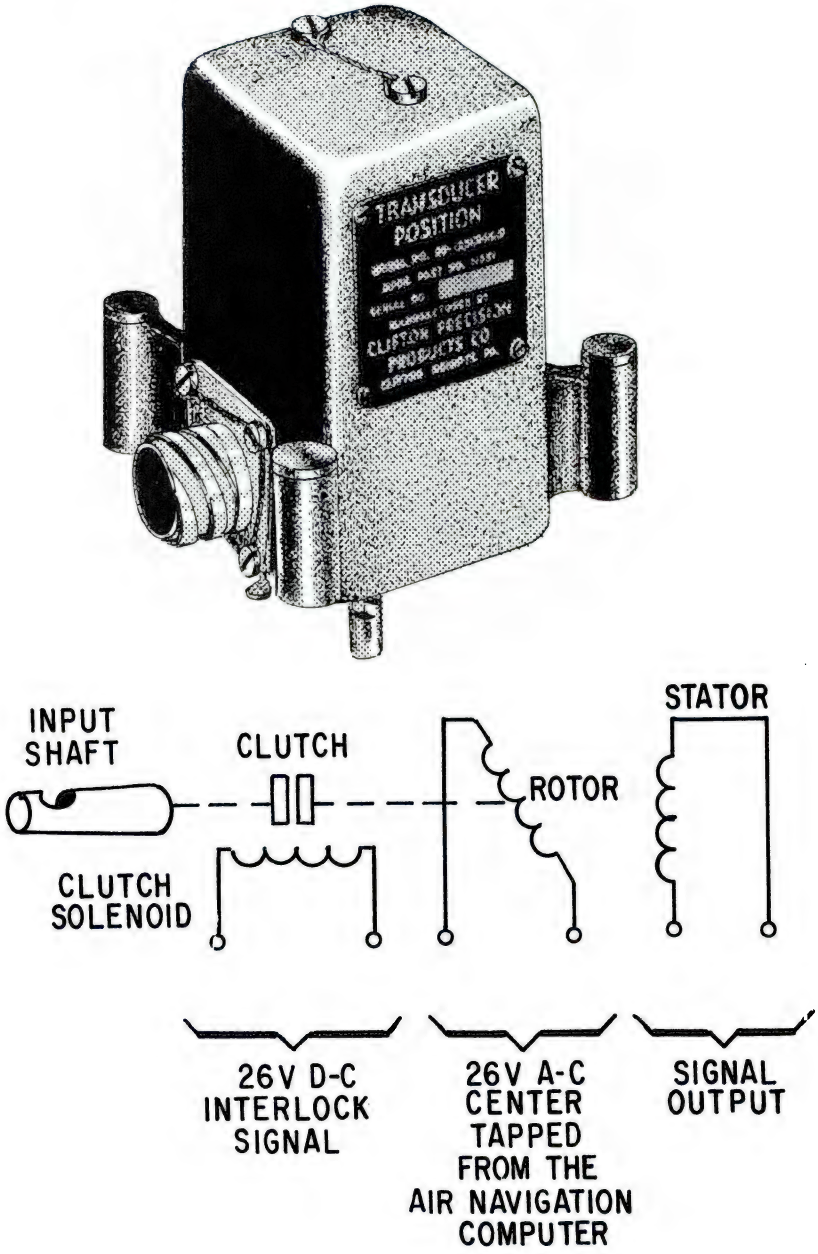

Figure 10-4.—Position transducer.

zero position when the clutch is deenergized. Rotation of the input shaft with the clutch deenergized does not affect transducer operation.

Flaperon Actuator

Each flaperon actuator (fig. 10-5) is a tandem arrangement of two double-acting power pistons mounted on a common rod. A valve section on the cylinder housing contains two tandem power valves that meter flow from separate hydraulic systems to the cylinder. Inputs are introduced at the valve shuttle from the flaperon gearing mechanism through the load relieving bungee unit. This actuator is similar in design and function to the stabilizer actuator.

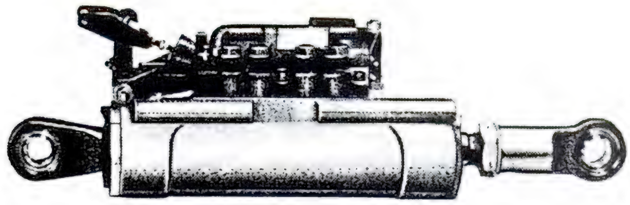

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Figure 10-5.—Flaperon actuator.

Flaperon Autopilot Actuator

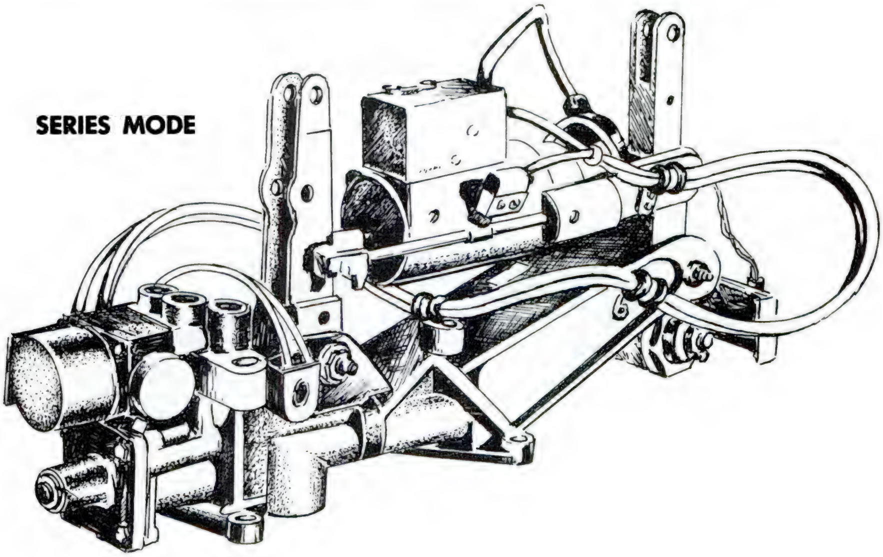
The flaperon autopilot actuator (fig. 10-6) controls the movement of the flaperons in response to mechanical commands from the pilot and to electrical commands from the AFCS. The flaperon autopilot actuator consists of a series mode solenoid valve, electrohydraulic servo valve, actuator pistons and rod, series link with transducer, input and output levers, and a load limiting element. The actuator operates in two modes—manual and series.

In the manual mode, the series mode valve solenoid is deenergized and no fluid is ported to any portion of the actuator. The series link cylinder contains two spring-loaded pistons that clamp the two pistons to the rod to form a rigid link. Input motions from the control stick are then transferred directly from the input lever to the output lever through the series link. The actuator piston rod is free to idle in this mode and is supported by ball bushings to minimize friction.

When operating in the series mode, the series mode valve is energized from the AFCS cockpit controller. This ports hydraulic system pressure to the electrohydraulic servo valve, the actuator cylinder, and the series link.

Rudder Actuator

The rudder actuator (fig. 10-7) is similar in design and function to the stabilizer and flaperon actuators. A valve section on the cylinder housing contains two tandem power valves that meter flow from the separate hydraulic systems



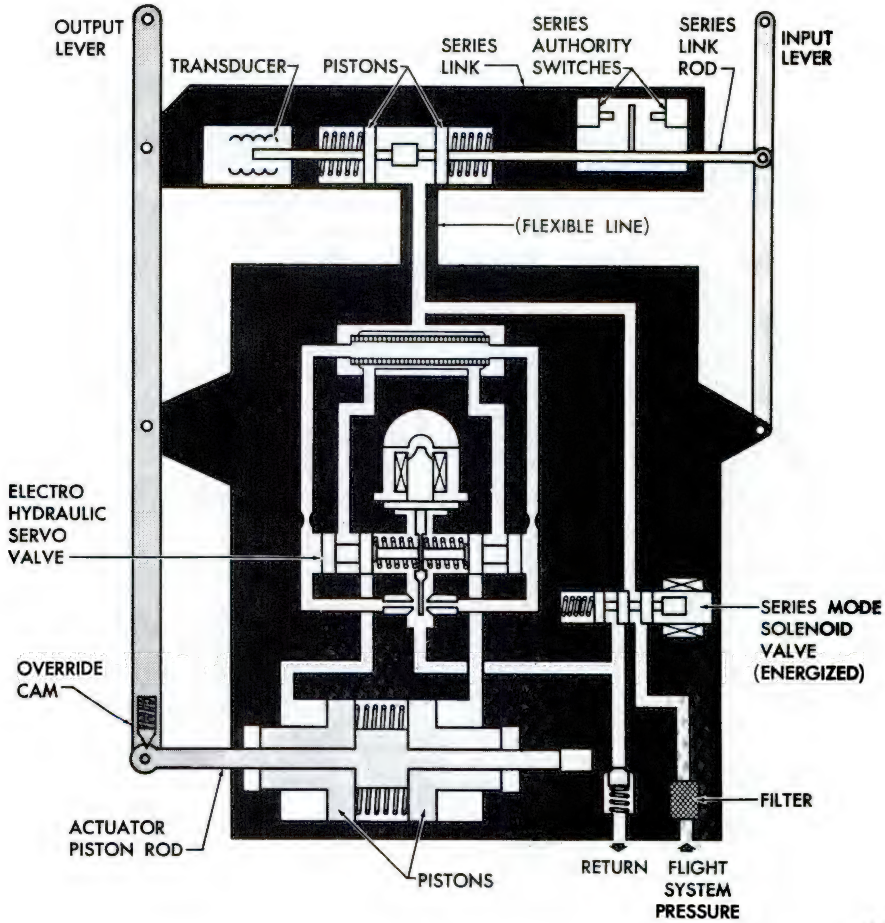


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Figure 10-6.—Flaperon automatic pilot actuator.

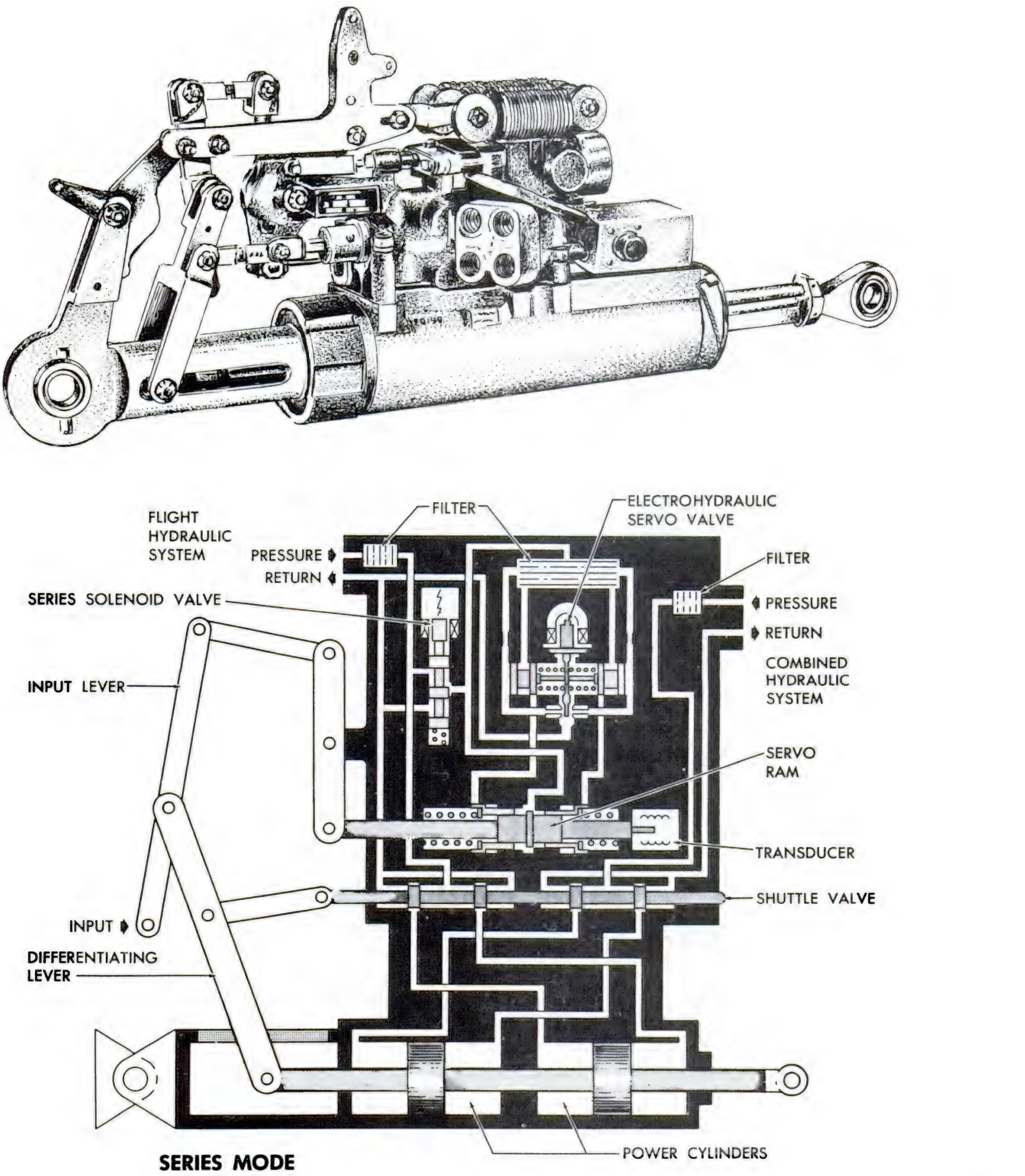

Figure 10-7.—Rudder actuator.

to the cylinders. The assembly includes a power shuttle valve, electrohydraulic servo valve, series (mode) solenoid valve, servo ram, mechanical input and differentiating levers, and a linkage stop mechanism. This actuator operates in two modes—manual and series.

When operating in the manual mode, the series (mode) solenoid valve is deenergized and no fluid is ported to the servo valve or the servo ram. Centering springs hold the servo ram at neutral, thereby fixing the position of the auxiliary link. Rudder-pedal motion is introduced through the input lever to the shuttle valve to port hydraulic flow to stroke the piston. A differentiating lever sums the rudder position with the rudder-pedal position to reduce the valve flow to zero.

A cam stop arrangement limits rudder movement to $\pm 4^\circ$ displacement from neutral for clean flight configuration. These stops are on the actuator and act on a roller on the input lever to the valve shuttle. Since this lever represents the summing point for the rudder-pedal and the AFCS inputs, the total rudder motion due to both rudder-pedal and AFCS inputs cannot exceed the 4° limit.

When operating in the series mode, the energized series (mode) solenoid valve ports pressure to the electrohydraulic servo valve and to the unlock section of the servo ram. Electrical signals from the AFCS are applied to the coils of the torque motor in the servo valve. Hydraulic flow from the servo valve varies with the differential current input. This flow drives the servo ram, which is connected through intermediate links to the differentiating lever. This lever sums servo-ram inputs with rudder-pedal inputs, introducing an error signal at the power valve shuttle, through the input lever. This displacement ports hydraulic flow to move the piston rod, in turn reducing the error to zero through the differentiating feedback link.

A transducer on the centerline of the servo ram provides servo-ram-position information to the AFCS. The series mode authority of the AFCS is $\pm 4^\circ$ of rudder motion from the pilot-commanded position. In the clean configuration, this authority is restricted to a maximum of 4° from neutral by the cam stop.

A summary of the electrohydraulic actuator operation, tying together actuator and AFCS operating modes, is shown in table 10-1.

SENSORS

The AFCS receives error or correction signals from the sensors (auxiliary and AFCS) for flight stabilization, attitude hold, and flight-path control. (See fig. 10-8.)

The AFCS signal coupling channels amplify, shape, and mix the error and correction signals to provide a proportional deflection of each of the aircraft control surfaces. The control system, divided into the AFCS servosystem and the

Table 10-1.—Summary of actuator operations.

AFCS Mode of operation	Actuator operation			Actuator manual inputs		
	Stabilizer	Flaperon autopilot	Rudder	Stabilizer	Flaperon autopilot	Rudder
Stability augmentation	Series	Series	Series	Control stick	Control stick	Rudder pedals
Attitude hold	Series	Series	Series	The axes revert to AFCS		
Altitude hold	Series	—	—	control on release of		
Mach hold	Series	—	—	the control stick or by		
Return to level	Parallel	Series	Series	controller switching.		(None)
Command	Parallel	Series	Series			
Ground controlled	Series	Series	Series			
Bombing (TPQ-10)	Series	Series	Series			

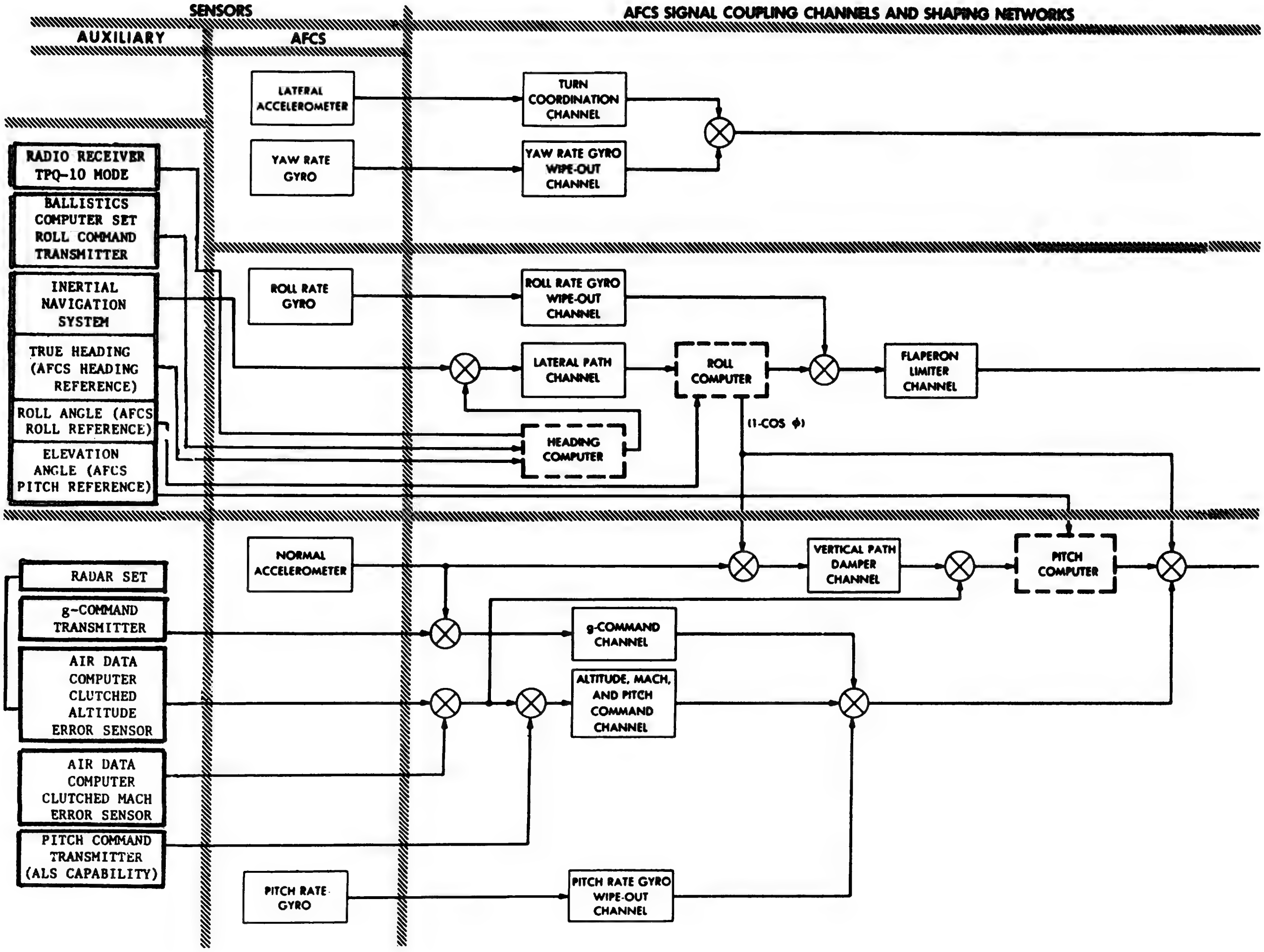

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Figure 10-8.—AFCS simplified schematic diagram.

aircraft control system, provides the electrohydraulic and mechanical coupling to deflect each control surface. The AFCS servosystem provides electrohydraulic power amplification of the shaped error and command information for each aircraft control axis. Each aircraft control system (hydraulic power actuator and control linkages) is proportionally driven by the output of the appropriate AFCS servosystem or through linkages from the pilot's manual inputs (stick or rudder pedals).

The sensors consist of the following components:

1. Lateral accelerometer.
2. Normal accelerometer.
3. Roll rate gyro.
4. Yaw rate gyro.
5. Pitch rate gyro.

In addition to the AFCS sensors, the system receives inputs from auxiliary sensors, which consist of the following:

1. Ballistic computer set.
2. Inertial navigation system.
3. Air data computer.
4. Ground controlled bombing system.

Rate Gyroscope

Aircraft yaw, pitch, and roll rates are detected and measured by the rate gyroscope.

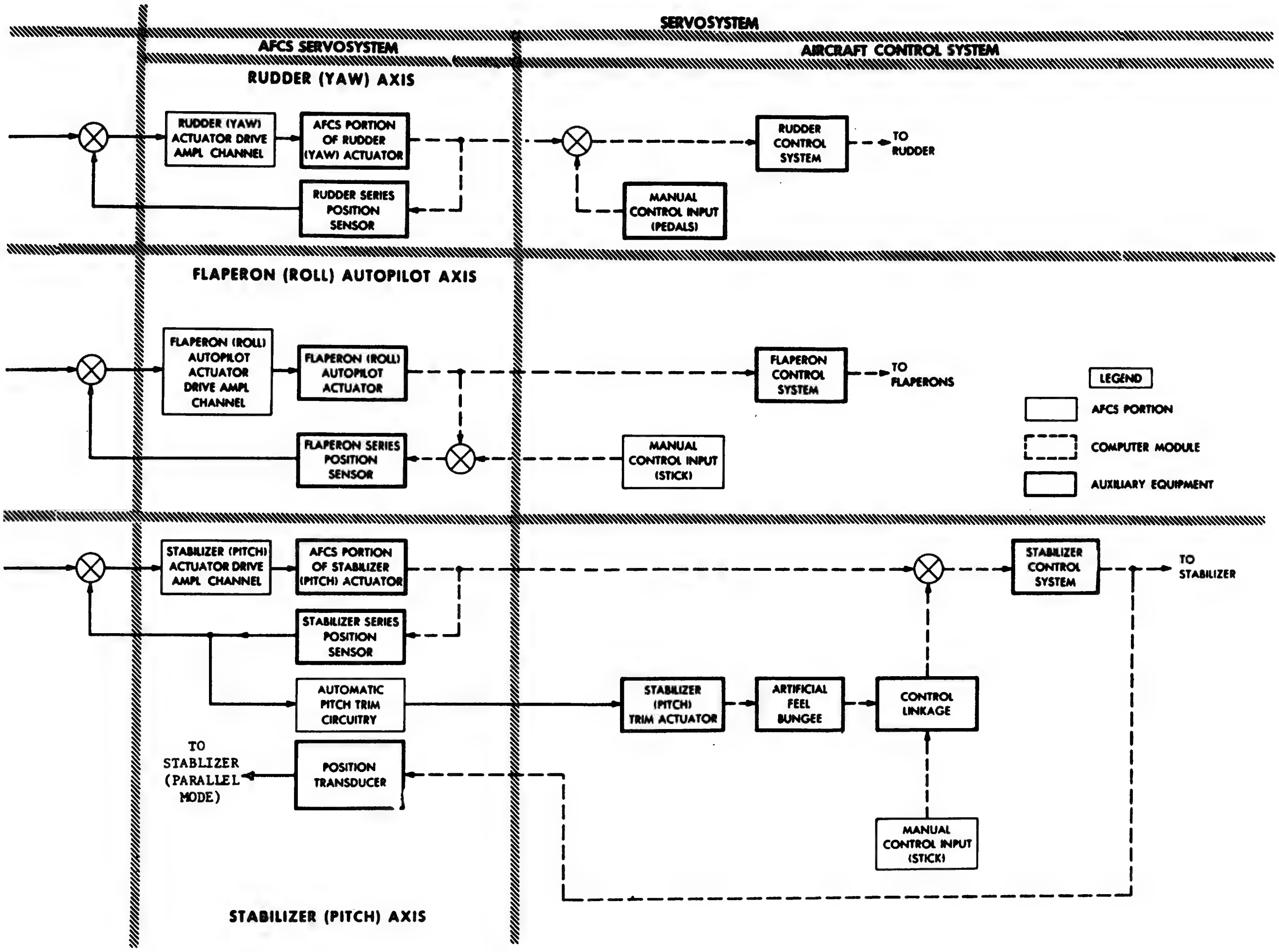

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Figure 10-8.—AFCS simplified schematic diagram—Continued.

These rate data are supplied to the air navigation computer for three-axis damping. The rate sensing device for each of the three axes consists of a miniature rate gyro (fig. 10-9). Roll rate gyro (B1), pitch gyro (B2), and yaw rate gyro (B3) are physically identical, integral assemblies. They differ only in respect to calibration, alinement, range, sensitivity, and natural frequency. Each gyro measures angular rate by the proportional precessional torque generated by the rate about the gyro input axis.

Internally, each rate gyro consists of a small viscous-damped, single-degree-of-freedom gyro (stator, rotor, and gimbal) with a differential transformer pickoff. The gyroscopic element of each gyro is the spherical rotor or a synchronous motor. The rotor is mounted in a gimbal frame and is spun at high speed about its spin axis. The gimbal is flexible mounted in the case and is free to rotate about an output axis which is perpendicular to both the spin axis and the input axis. The rotational freedom about this axis is limited by a torsion restoring spring that couples the gimbal to the case. Between the gimbal and case is a viscous damper. The gyro gimbal also carries the pickoff rotor on an extension along its output axis. The pickoff senses the relative angular displacement of gimbal and case.

The schematic representation of each rate gyro (B1, B2, and B3) is shown in figure 10-9. The stator windings of the motor receive 26-volt,

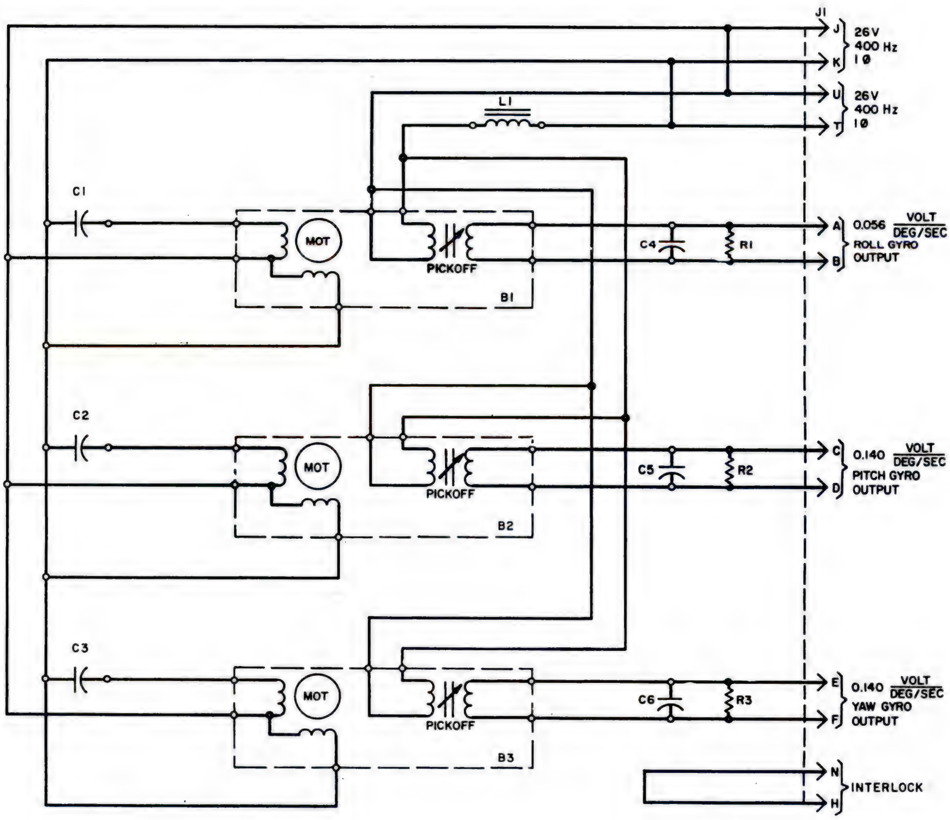

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Figure 10-9.—Rate gyroscope.

400-Hz, single-phase excitation. Since the gyro motor is operated from single-phase voltage, its leading motor phase is connected to the excitation supply through a 1.0-microfarad capacitor (C1, C2, and C3). The pickoff primary is excited with voltage from the motor excitation through choke L1. This choke compensates for pickoff gain changes produced by excitation frequency and by temperature variations. It also reduces the effect of harmonic distortion in the excitation supply.

With the pickoff rotor in its zero or neutral position, the mutual inductance is zero; a current flowing in the pickoff primary causes essentially no voltage in the secondary (output) winding. As the pickoff rotor is turned one way or the other by gyro gimbal deflection about its output axis (due to the laws of gyroscopic precession), a proportional mutual inductance (positive or negative, depending upon the direction of deflection from neutral position) is introduced. Hence, a voltage proportional to this mutual inductance is produced in the pickoff secondary due to a current flowing in its primary. The output voltage is proportional to the aircraft's angular velocity input to the gyro in the particular axis. For calibration, resistor R1 and capacitor C4 are connected across the roll rate gyro output (resistor R2 and capacitor C5 are connected similarly for the pitch rate gyro, and resistor R3 and capacitor C6 for the yaw rate gyro).

Accelerometer Transmitter

Two accelerometers are used in the AN/ASW-16 AFCS—the lateral and normal accelerometers. The lateral accelerometer generates a signal proportional to aircraft lateral acceleration and is used for turn coordination. The normal accelerometer generates a signal proportional to the normal (vertical) acceleration that is used for altitude or Mach hold vertical path damping, and also as the g-command reference. The two accelerometers are physically the same, and their operation is identical. Therefore, only the lateral accelerometer is discussed.

The lateral accelerometer is shown in figure 10-10 (A). A cutaway view of the lateral accelerometer is shown in figure 10-10 (B). The unit consists of a cast housing assembly, a sensitive element assembly, bellows, and calibration resistors (R51, R52, and R53). The sensitive element assembly has an E-pickoff, an armature and armature support, flexure springs, and a backplate. The sensitive element assembly and bellows are sealed inside the housing, which is filled with damping fluid. The damping fluid provides viscous damping during motion of the armature. The lateral accelerometer is calibrated by means of null shift and range adjustments, selected resistors (R52 and R53), and variable resistor R51, which is mounted in a horizontal plane.

The E-shaped core of the E-pickoff (fig. 10-10 (C)) has an excitation winding (winding A) and a compensation winding (winding B) on the center leg, and a signal output winding (coils A and B) on each of the outer legs.

Excitation voltage (120-volt, 400-Hz, single-phase) is applied to winding A (in series with resistor R52). The signal output windings (coils A and B), differentially connected to yield a null output under static (zero g) conditions, produce a phase-sensitive output acceleration signal.

As the aircraft accelerates in the sensitive (lateral) direction, the suspended armature tends to remain behind due to its inertia, thus varying the reluctance of the magnetic circuit set up by the E-pickoff windings and armature. The armature completes the magnetic circuit through a small airgap. The relative motion between the armature and E-pickoff varies the reluctance through the signal output windings, which results in a signal that is proportional to acceleration. In operation, the output voltage is either in phase or 180° out of phase with the excitation, depending on the direction of acceleration.

AIRCRAFT CONTROL STICK

The aircraft control stick (fig. 10-11 (A)) is composed of a handle (pilot grip) and cable assembly and a transducer housing. The handle and cable assembly contain the following switches: nosewheel steering, weapon release, trim, attack commit, uncage boresight, and autopilot off. Roll and pitch control forces, applied by the pilot, are transmitted to the aircraft control linkage via the transducer. The stick provides the pitch and roll switching for control stick steering.

The operating parts of the aircraft control stick are shown in figure 10-11 (B). A spherical bearing at the top of the transducer permits moving the handle in any direction with respect to the transducer housing. Moving the handle in one direction causes a shaft to move in the

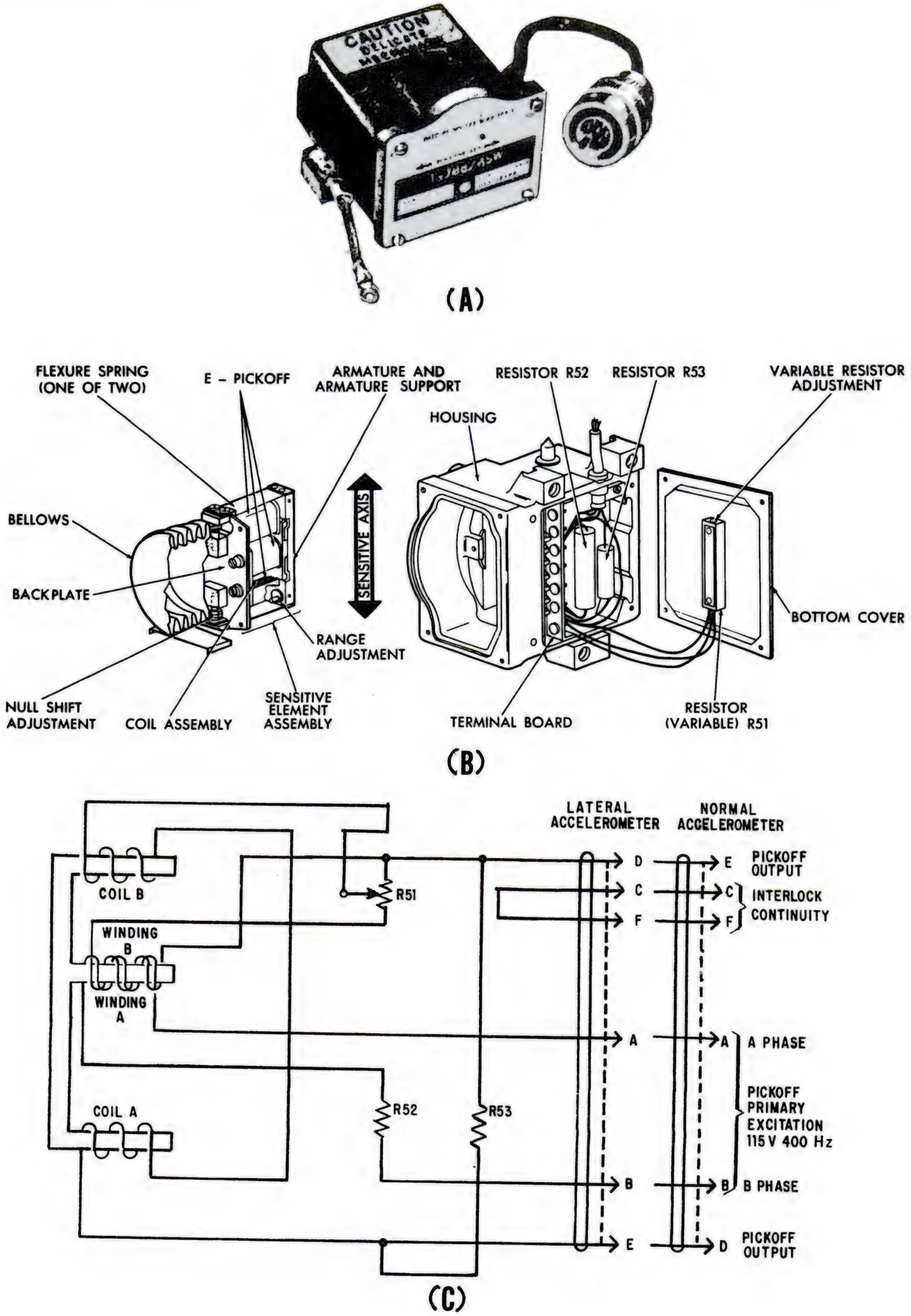

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Figure 10-10.—Lateral accelerometer.

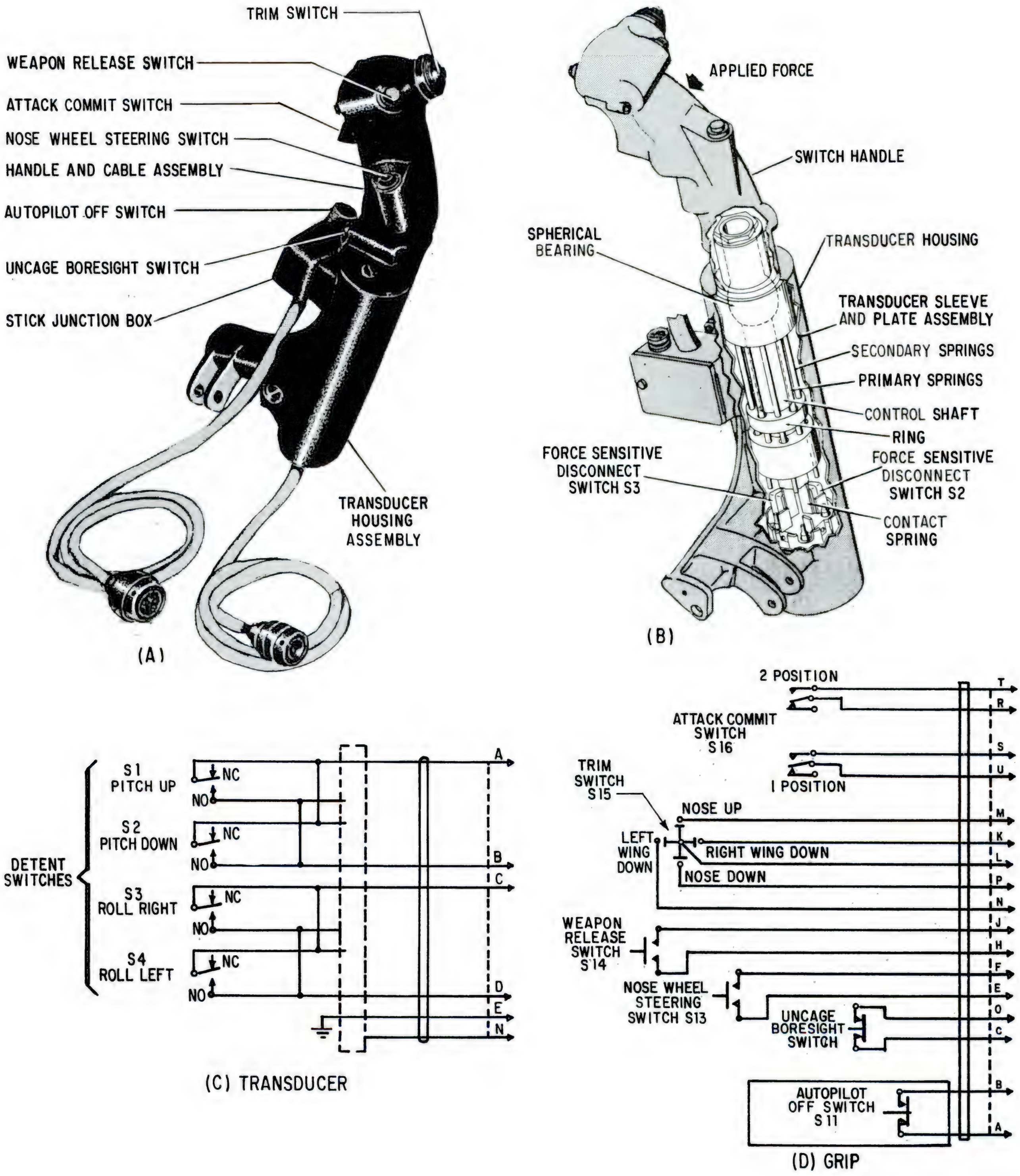

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Figure 10-11.—Aircraft control stick.

opposite direction. The shaft is held in central position by means of four-rod shaped primary springs. Bearing against the lower end of the shaft are four switch actuators.

Moving the handle beyond the detent force position causes the shaft to contact a ring holding four secondary springs. If the applied force is increased further, movement is communicated to the transducer sleeve and thence through the transducer housing to the control column.

The shaft and associated parts are of sufficient weight to counterbalance the handle about the spherical bearing. Assume that a force is applied to the handle for pitchdown action as shown in figure 10-11 (B). The shaft acts through a switch actuator to close switch S2, thereby providing a pitchdown interlocking system disconnect signal. Further movement of the handle, beyond the limit of the transducer mechanism, causes movement of the control column. If the pilot pulls the stick toward him, a switch (located opposite S2) is closed, providing a pitchup interlocking signal. When the force is removed from the handle, the shaft is returned to central position by the spring action. If the pilot forces the handle to the left, a switch is closed for a left-roll interlock signal. If the stick is moved to the right, a switch is closed for a right-roll interlock signal.

The two pitch disconnect switches (S1, pitchup; S2, pitchdown, fig. 10-11 (C)) are both single-pole, double-throw switches. With no force applied to the stick, an open circuit exists between terminals A and B. When a force (pitchup or pitchdown) equivalent to or greater than 1.4±0.3 pounds is applied to the stick, continuity exists between terminals A and B. The two roll disconnect switches (S3, roll right; S4, roll left) are similar. With no force applied to the stick, an open circuit exists between terminals C and D. When a roll force (for roll right or roll left) equivalent to or greater than 1.1±0.3 pounds is applied to the stick, continuity exists between terminals C and D.

The autopilot off switch (S11, fig. 10-11 (D)) is a normally closed, momentary-break-contact pushbutton switch. With the switch in the normally closed position, continuity exists between pins A and B.

The uncage boresight switch (S12) is a momentary-open contact, normally closed, pushbutton switch. With the switch in the normally closed position, continuity exists between pins C and D.

The nosewheel steering switch (S13) is a momentary-close-contact, normally open, pushbutton switch. With the switch in the normally open position, an open circuit exists between pins E and F.

The weapon release switch (S14) is a pushbutton, momentary-close-contact, normally open switch. With the switch in the normally open position, an open circuit exists between pins H and J.

The trim switch (S15) is a four-way button type. With the switch in the neutral (center) position, an open circuit exists between pins L and pins K, M, N, and P. With the trim button moved for noseup trim (button displaced down), continuity exists between pins L and M; with the trim button moved for nosedown trim (button displaced up), continuity exists between pins L and P; with the trim button displaced to the left, continuity exists between pins L and N; and with the trim button displaced to the right, continuity exists between pins L and K.

The attack commit switch (S16) is a two-position, double-pole, double-throw, trigger switch. With the switch in the normally open position, an open circuit exists between pins R and T and U and S. When the trigger is squeezed to the first position, continuity exists between pins U and S. When the trigger is squeezed to the second position, continuity exists between pins R and T.

The AFCS function of the switches in the aircraft control stick is presented in table 10-2.

AUTOMATIC PILOT ENGAGING CONTROLLER

The automatic pilot engaging controller, located in the cockpit, is a pilot-operated switching device that is used to select operational modes. (See fig. 10-12.) The switches of the component serve as manually operated interlocks in establishing the circuitry required for system operation in accordance with the operational mode selected. The controller consists of three solenoid-held toggle switches (ON-OFF, CMD, and AUTO STAB-AUG) two solenoid-held, square pushbutton switches (ALT and MACH) and a round, momentary-on pushbutton switch (RETURN TO LEVEL). The edge-lighted panel incorporates seven inbedded panel lamps.

The ON-OFF switch (S26) is a single-pole, double throw, magnetic hold-in toggle switch.

Table 10-2.—Function of switches in aircraft control stick.

Switch	Nomenclature	Purpose	Settings and functional indications
S11	AUTOPILOT OFF switch	Emergency disengage switch for all AFCS switches.	Momentary on switch. (Diagonal striping of yellow and black.) Actuation causes all controller switches to disengage or move to OFF positions automatically.
S15	Trim switch	Position stabilizer and flaperon control surfaces for desired trim.	Forward, nosedown trim; aft, noseup trim; left, left wing down trim; right, right wing down trim.
S2	Stick pitchdown detent switch	Disengages pitch axis attitude control and roll damper for manual override stick steering.	Pilot force (1.1 lb) actuates the switch which cuts out AFCS attitude control for the duration of applied stick force. If AUTO STAB-AUG switch is in AUTO mode, and either ALT or MACH switch is engaged, only the AUTO switch will remain engaged upon application of stick force. If the command switch is engaged, and the ballistic computer operation in effect, the command switch remains engaged so that ballistic computer set operation is automatically restored upon release of stick force. If the command switch is engaged, and ALS data link operation is in effect, the command switch disengages upon application of stick force and may be manually reengaged after release of stick force.
S1	Stick pitchup detent switch.	Disengages pitch axis attitude control for manual override stick steering.	(See S2.)
S3	Stick roll right detent switch.	Disengages roll axis attitude control for manual override stick steering.	Pilot force (1.1 lb) actuates the switch. The switch cuts out all roll damper attitude control for the duration of applied stick force. If the command switch is engaged, the switch will remain engaged so that roll command operation is restored upon release of stick force. If TPQ-10 ENGAGE switch is actuated, it disengages upon application of stick force.
S4	Stick roll left detent switch.	Disengages roll axis attitude control and roll damper for manual override stick steering.	(See S3.)

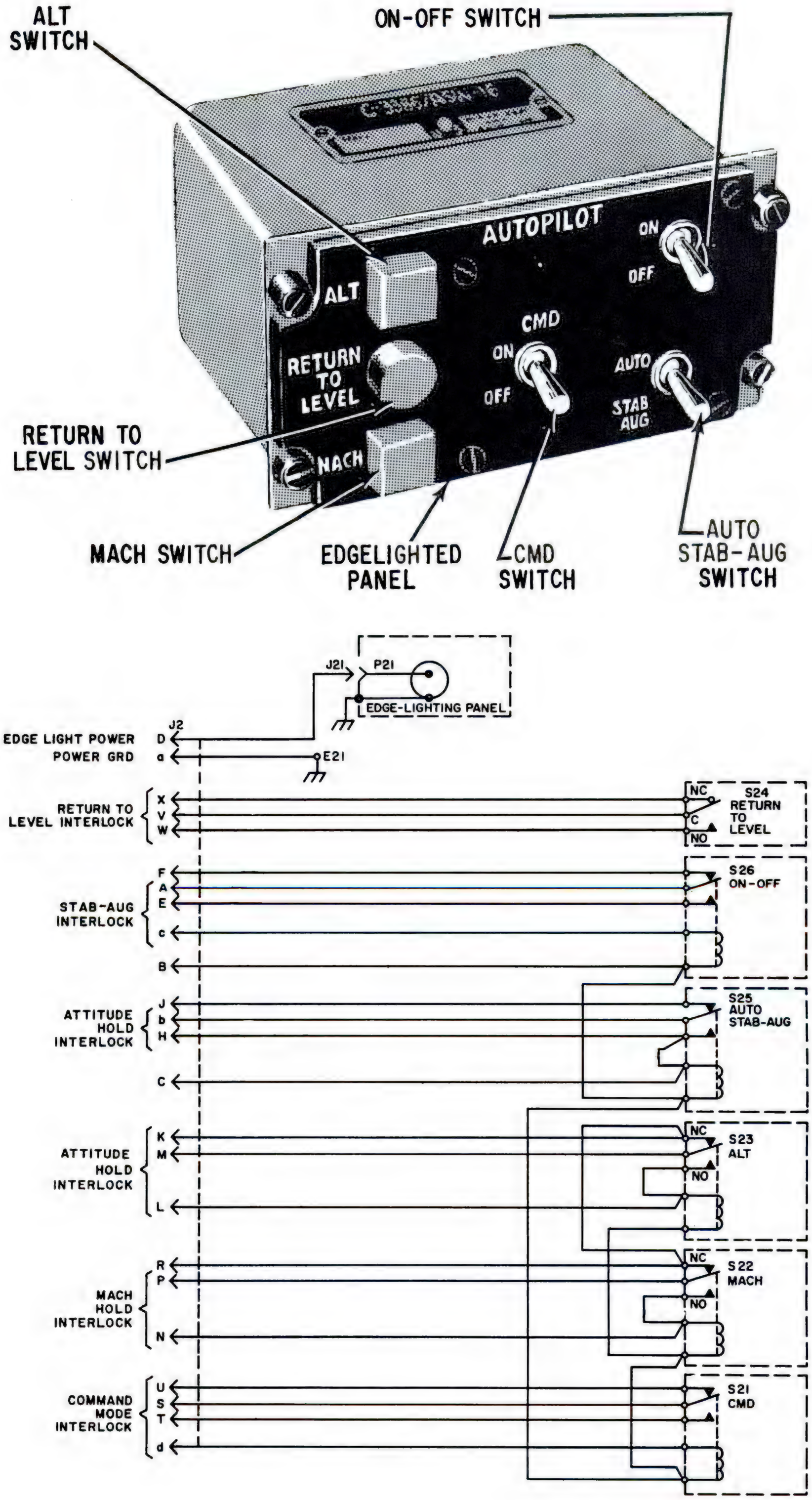

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Figure 10-12.—Automatic pilot engaging controller.

This switch, used to engage interlock circuitry and to apply 28-volt d-c interlock voltage to the AFCS, has an ON and an OFF position. With the switch in the OFF position, continuity exists between A and F; with the switch in the ON position, continuity exists between A and E. With no power applied, the switch returns to the OFF position when moved to the ON position and released. With power applied, a 28-volt d-c input impressed on A is diverted to an output across E when the switch is moved from the OFF to the ON position. In normal system operation, this voltage is impressed through external interlock circuitry. The switch remains at ON and returns to OFF only when voltage is removed or when the switch holding solenoid is manually overridden.

The AUTO STAB-AUG switch (S25) is a single-pole, double-throw, magnetic hold-in toggle switch. This switch, used to engage the attitude hold mode, contains an AUTO and a STAB-AUG position. With the switch in the STAB-AUG (disengaged) position, continuity exists between b and J. With the switch in the AUTO position, continuity exists between b and H. With no power applied, the switch returns to the STAB-AUG position when moved to the AUTO position and released. With power applied, a 28-volt d-c input impressed on b is diverted to an output across terminal H when the switch is moved from the STAB-AUG position to the AUTO position. The switch remains at AUTO and returns to STAB-AUG only when voltage is removed or when the switch holding solenoid is manually overridden.

The CMD (command) switch (S21) is a single-pole, double-throw, magnetic hold-in toggle switch. This switch, used to engage the command mode, contains an ON and an OFF position. With the switch in the OFF position, continuity exists between S and U; with the switch in the ON position, continuity exists between S and T. With no power applied, the switch returns to the OFF position when moved to the ON position and released. With power applied, a 28-volt d-c input impressed on S is diverted to an output across T when the switch is moved from the OFF to the ON position. In normal system operation, 28-volts d.c. is impressed on d through the external interlock circuitry. The switch remains at ON and returns to OFF only when voltage is removed from d or when switch holding solenoid is manually overridden.

The ALT switch (S23) is a double-pole, double-throw, magnetic hold-in, square pushbutton switch, used to engage the altitude hold mode. With the switch in the disengaged (not depressed) position, continuity exists between K and M. With the switch in the engaged (depressed) position, continuity exists between L and M. With no power applied, the switch returns to the disengaged position when depressed to the engaged position and released. With power applied, the switch directs a 28-volt d-c input (impressed on M) to an output across L when the switch is depressed to the engaged position. The switch remains engaged and disengages only when voltage is removed.

The RETURN TO LEVEL switch (S24) is a double-pole, double-throw, momentary-close round pushbutton switch used to engage the automatic return to level flight mode. With the switch in the OFF (not depressed) position, continuity exists between X and V. With the switch in the engaged (depressed) position, continuity exists between V and W. With or without power applied, the switch returns to the OFF position when depressed and released.

The MACH switch (S22) is a double-pole, double-throw, magnetic hold-in, square pushbutton switch, used to engage the Mach hold mode. With the switch in the disengaged (not depressed) position, continuity exists between P and R. With the switch in the engaged (depressed) position, continuity exists between N and P. With no power applied, the switch returns to the disengaged position when depressed and released. With power applied and the switch depressed to the engaged position from the disengaged position, 28-volt d-c input from P is diverted to an output across terminal N. The switch remains engaged and disengages only when voltage is removed.

AIR NAVIGATION COMPUTER

Since all operational functions of the automatic flight control system are channeled through the computer, it is the heart of the entire system. The computer couples, shapes, and amplifies stability augmentation and automatic flight control signals. These signals are used to operate the actuators previously described. A-c control inputs and error signal inputs are accepted from auxiliary subsystems

and sensors. These inputs are obtained from the inertial navigation system, ballistic computer, air data computer, ALS data link, and radio receiver. Inputs are also obtained from pitch, roll, and yaw actuator position sensors and from AFCS sensors, including the normal and lateral accelerometers and the rate gyroscope. A-c excitation voltages are also supplied by the computer to all of the components and auxiliary equipment which supply inputs to the AFCS. Signal switching operations are controlled by the computer through an interlocking relay arrangement in connection with the controller mode selection switches. Provisions for gain adjustments of the major system parameters are provided through a calibration board mounted on the front of the computer. The computer is comprised of an equipment rack and seven amplifier modules. (See fig. 10-13.) Each of the seven modules contain submodules, some of which are identical and are interchangeable between modules.

Command Coupler Module

Command and coordination signals from various sensors and reference units are received by the command coupler. These signals are summed, shaped, amplified, and limited, and then distributed to other circuitry for execution of the commands. To accomplish these functions, the command coupler contains circuitry for the following functional channels:

1. Altitude, Mach, and pitch command channel.
2. Vertical path damping channel.
3. Turn coordination channel.
4. Lateral path channel.
5. G-command channel.
6. Flaperon limiter channel.

Each of the channels is illustrated in figure 10-14. During the following discussion, reference should be made to this illustration.

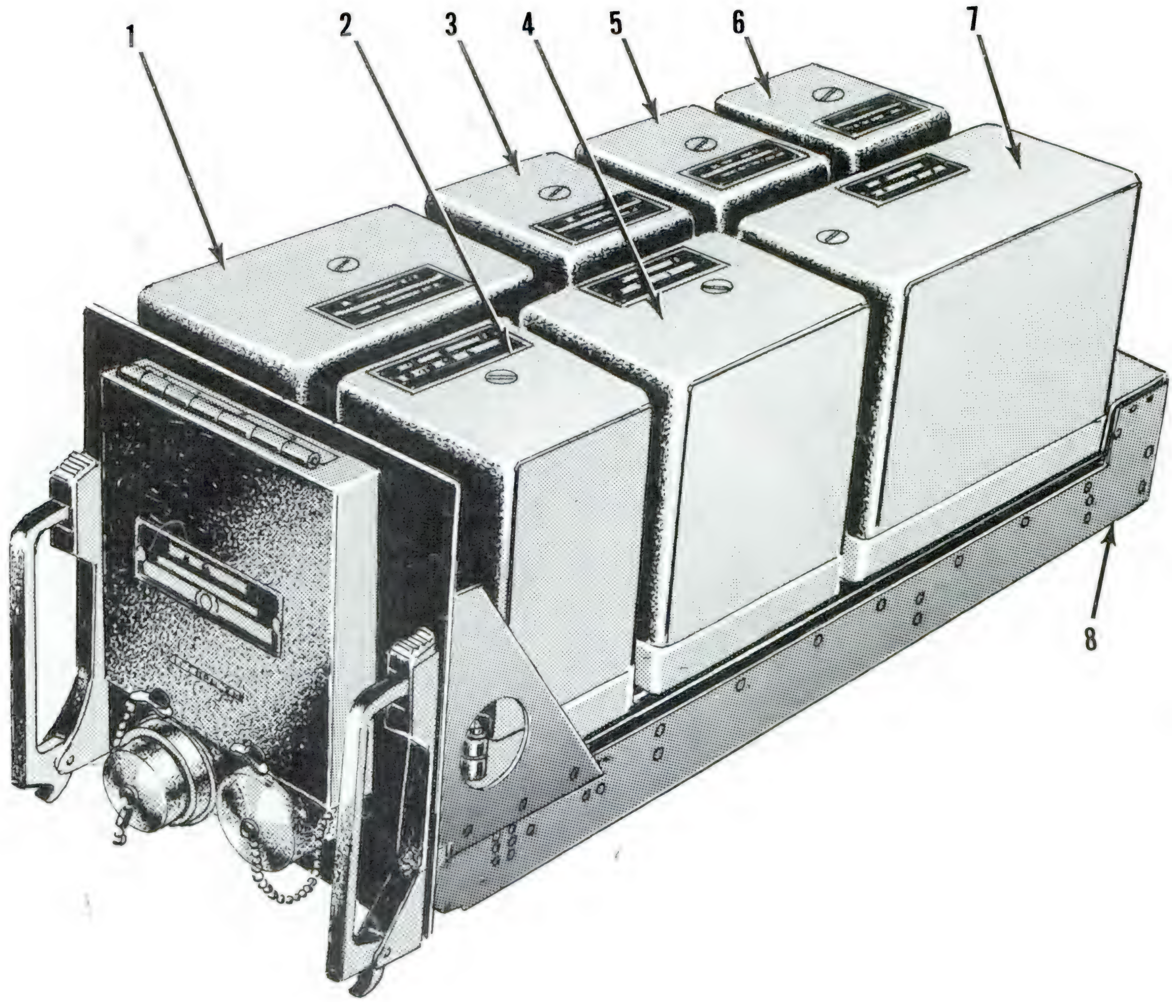
ALTITUDE, MACH, AND PITCH COMMAND CHANNEL.—Altitude, Mach, and pitch command information error signals are applied to demodulator-modulator Z100-5. In the demodulator portion, the input signal is converted to d.c. which is porportional to the input, with the polarity dependent on the phase of the input. The output of the demodulator is passed through a low pass filter (C5011) to the input of the modulator. The modulator converts the varying d-c signal to a modulated, 400-Hz a-c signal. The output of the modulator is passed through a limiter which limits its magnitude. The limited a-c signal is fed to the AFCS servosystem to establish a pitch attitude to bring the aircraft back to the desired reference.

VERTICAL PATH DAMPING CHANNEL.—The normal accelerometer and the $(1 - \cos \phi)$ are signals applied to demodulator-modulator Z100-7. The signal is converted to d.c., passed through high and low pass filters (C5017 and C5018, respectively), and modulated. The high pass filter (C5017) is used to block steady-state inputs such as nulls. The low pass filter (C5018) is used to provide a low impedance path to ground for high frequency signal inputs (noise). The a-c output signal is fed to the pitch computer, operating as an integrator to provide vertical path damping in the altitude hold and Mach hold modes.

TURN COORDINATION CHANNEL.—The lateral accelerometer signal is applied to the demodulator section of Z100-8 where it is converted to d.c. This d-c signal is fed to a displacement section and an integral section. In the displacement section, the d-c signal is filtered with a short time constant filter (R5012 and C5016) to eliminate noise. The signal is then converted to a.c. in the modulator section of Z100-8. In the integral section, the d-c signal is filtered heavily (R807, C5014, and C5015) and then converted to a.c. in the modulator section of Z800-2. The displacement and integral signals are then summed at the input to the buffer amplifier section of Z800-2. The combined signal is fed to the AFCS servosystem to provide rudder deflections for turn coordination.

LATERAL PATH CHANNEL.—Heading computer control transformer heading reference (through the air data computer Mach potentiometer and an emitter follower) or roll command signals are applied to demodulator-modulator Z100-4. The particular signal, depending on AFCS mode, is converted to d.c., filtered, modulated to 400 Hz, and limited. A maximum bank angle is established by the limited output of Z100-4. This output is fed to the roll computer to command bank angles proportional to the error signal.

G-COMMAND CHANNEL.—The normal accelerometer signal and the g-command signal (through contacts of K5053) are applied to demodulator Z100-3. The error signal is converted to d.c. and filtered heavily in the same



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1. Pitch computer amplifier.
2. Flaperon (roll) servoamplifier.
3. Stabilizer (pitch) servoamplifier.
4. Roll computer amplifier.
5. Rudder (yaw) servoamplifier.
6. Heading computer amplifier.
7. Command coupler amplifier.
8. Equipment rack.

Figure 10-13.—Air navigation computer.

manner as in the integral section of the turn coordination channel. It is then converted to a.c. in the modulator section of Z800-1 and amplified in the amplifier section of Z800-1. The resultant output is fed to the AFCS to command stabilizer motions proportional to the integral of g-command error.

FLAPERON LIMITER CHANNEL.—Rate gyro and roll computer attitude reference signals are applied to the amplifier limiter Z1400. These signals are amplified in the amplifier section of Z1400 and applied to the limiter section of Z1400 to assure that the flaperon authority limit is not exceeded.

Roll Computer Module

The roll computer amplifier module accepts inputs from the aircraft roll attitude reference

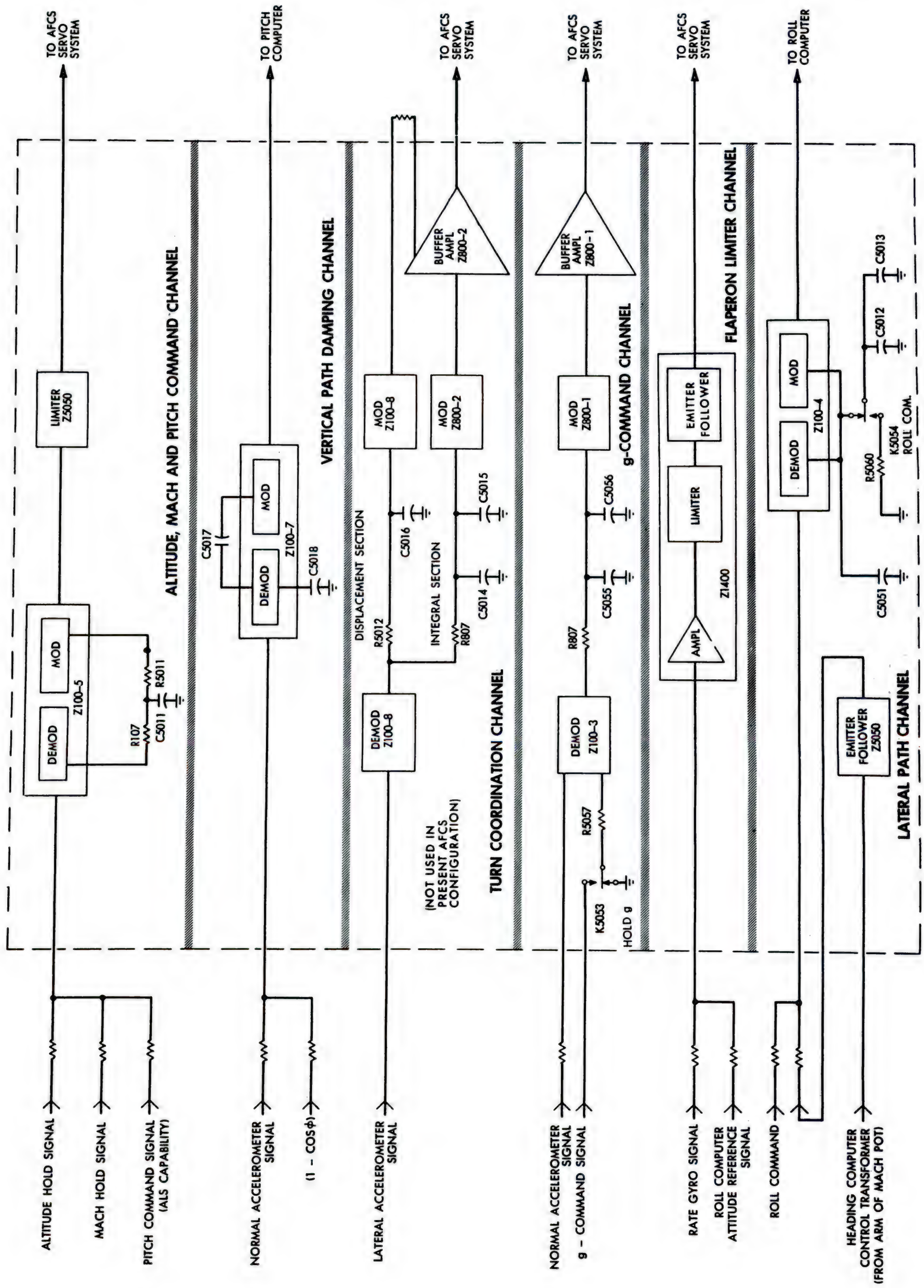

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Figure 10-14.—Command module functional channels block diagram.

and from the command coupler lateral path channel. The module output is applied to the roll servoamplifier module to command aircraft roll through flaperon deflection. The module incorporates a synchronization channel comprising a motor amplifier and servo assembly. The servo consists of a motor tachometer driving a control transformer, a sine-cosine resolver, and roll-position-sensing sector switches through a reduction gear train. (See fig. 10-15.) In addition, the module incorporates roll synchronization monitor circuitry, pitchup compensation circuitry for turns, five relays, and a power supply.

In the roll attitude synchronizing configuration, relays K3001, K3003, and K3004 are deenergized. The control transformer, which is connected back-to-back with the roll synchro transmitter of the inertial navigation system, senses changes in the roll attitude of the aircraft. The resulting error signal is fed to the input of the motor amplifier. The amplified signal drives the motor tachometer, which in turn drives the control transformer through a 525:1 gear ratio, thereby maintaining the control transformer output at a null. In order to keep this closed servo loop stable, the output of the tachometer is fed back and summed at the

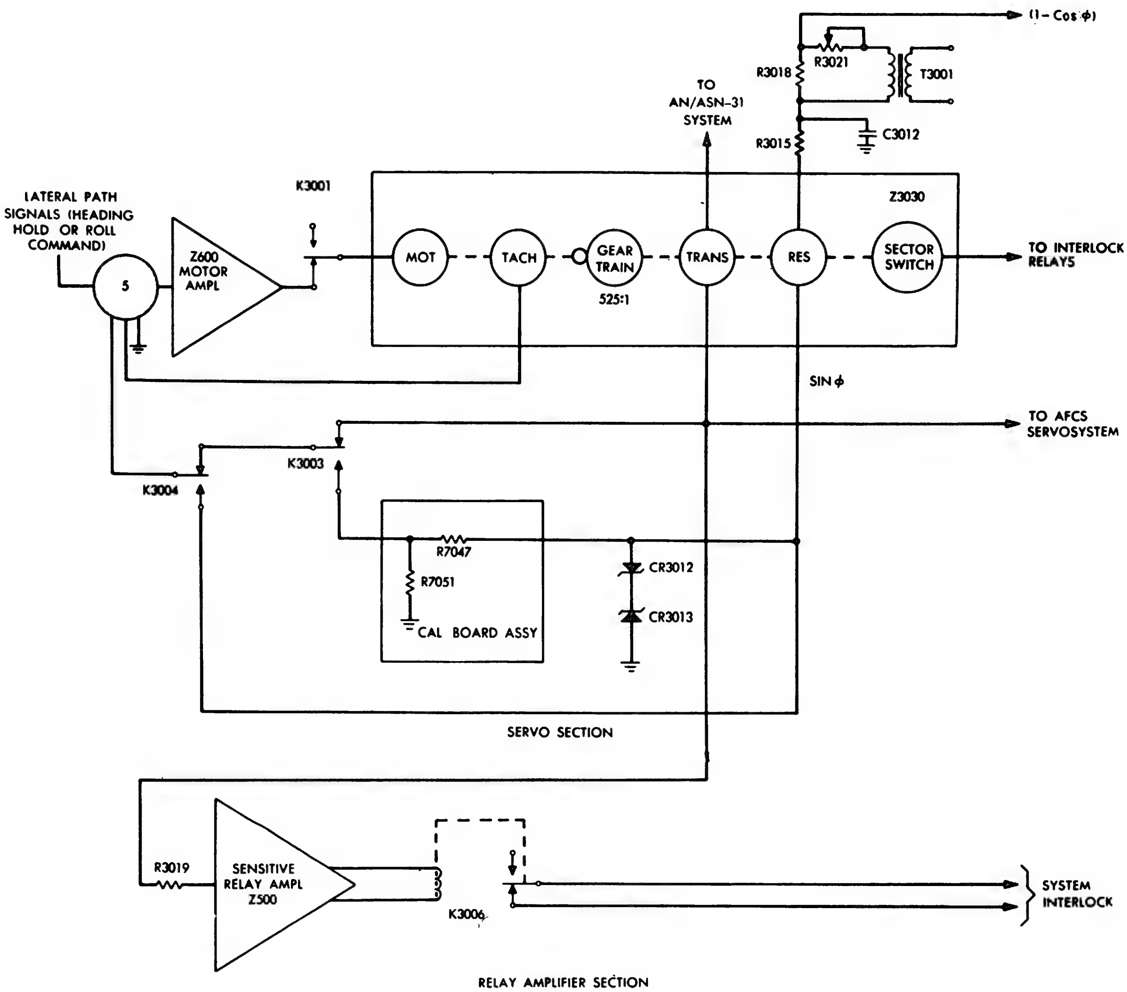

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Figure 10-15.—Roll computer module block diagram.

motor amplifier input to provide the necessary damping.

The attitude hold mode is engaged via the AUTO position of the AUTO STAB-AUG switch on the controller when the aircraft roll attitude is greater than 5° as sensed by the sector switch. Relay K3001 is energized, clamping the motor, thereby preventing any further synchronization and establishing a fixed roll reference. Deviations about this reference attitude are sensed by the control transformer and fed to the AFCS servosystem to perform the necessary corrective action to maintain the reference attitude.

The heading hold configuration and wing leveling is automatically selected when the attitude hold mode is engaged with the aircraft roll attitude between zero and 5°. In this mode, relay K3001 is deenergized, unclamping the motor; and relay K3004 is energized, inserting the sine output of the roll computer resolver into the input of the motor amplifier. The heading computer reference is clamped by means of interlocking relays. Deviations from this reference heading are sensed by the locked heading computer control transformer and fed to the input of the roll computer motor amplifier, thereby driving the motor, which in turn drives the resolver and the control transformer.

The resolver sine output is fed back to the motor amplifier input to cancel the error signal from the heading computer control transformer, and the roll computer control transformer output is fed to the AFCS servosystem to establish an aircraft bank angle. The resulting bank changes the aircraft heading, thereby reducing the heading error until it is zero. A wings-level condition is then established. In the TPQ-10 mode, the heading computer (operating as an integrator) generates heading errors proportional to ground commands that are inserted as inputs to the roll computer (in a manner identical to the heading hold mode) to command bank angle proportional to heading error. Roll command inputs to the roll computer also cause the servo section to function in a manner similar to that described for the heading hold mode; that is, command bank angle proportional to input roll command error.

In the roll back mode, the sector switch assembly, which rotates with the sine resolver, measures angular roll displacement from level flight. The upper limit on roll attitude hold is ± 60°. When the attitude hold mode is engaged with the roll attitude greater than ±60°, relay K3003 is energized through conducting segments on the sector switch. The resolver sine output is fed back to the motor amplifier input through a limiting network (CR3012 and CR3013) to establish a roll back to 60° rate. The control transformer output is fed into the AFCS servosystem that commands flaperon deflection to roll the aircraft back towards 60°.

The roll computer is clamped when the roll attitude returns to 60°, and this attitude is maintained as described in the attitude hold mode discussion. When the return to level switch on the controller is depressed, relay K3003 remains engaged (roll angle greater than 60°) or will become engaged (roll angle less than 60°) through rack interlocking relays. The aircraft rolls back at its established rate until the bank angle is 5°, at which point the heading hold configurations in the attitude hold mode or roll command in the command modes is reestablished.

The $(1 - \cos \phi)$ turn compensation signal is derived from the cosine winding of the servo section resolver. This winding provides an output voltage proportional to the cosine of angular roll displacement from level flight ($\cos \phi$). The signal is series-summed with transformer T3001 to provide a net output of zero volts at zero roll attitude ($\phi = 0°$). For roll displacement from level flight, this net output is then proportional to $(1 - \cos \phi)$. Resistor R3015 and capacitor C3012 correct the phase of the resolver to facilitate the summation with T3001. Resistors R3018 and R3021 adjust the output of T3001 to provide for a cancellation of the zero attitude resolver output.

The sensitive relay amplifier receives a constant input from the control transformer. When roll displacement between the stable platform roll reference and the control transformer exceeds 2°, the output signal from the amplifier energizes relay K3006, preventing engagement of the AFCS switch.

Roll Servo Module

The roll servoamplifier module (fig. 10-16) receives a rate gyro input, which is shaped and mixed with command and feedback signals for roll axis control. The output is supplied to a hydraulic servo-valve actuator which moves the flaperons as required.

The input from the roll rate gyro is a 400-Hz signal, whose phase and amplitude are dependent upon the direction of gyro precession

and the amount of precession. The input signal is coupled to the demodulator section of Z100-2, where it is compared with a 400-Hz reference voltage and changed to a varying d-c signal. The amplitude of the demodulator output is proportional to the input, and the polarity is dependent upon the phase. Capacitor C1053 offers coupling between the demodulator and the modulator, wiping out the d-c level caused by steady-state (constant amplitude) signals. The varying d.c. is converted to a modulated 400-Hz output, with zero output for steady-state inputs. Since the demodulator is sensitive only to voltages in phase, or 180° out of phase with the reference voltage, quadrature voltage rejection takes place and the output is a "clean" signal.

The summing point (7) parallel-sums the input from the wipe-out channel with other roll command and feedback signals as shown in figure 10-16. The summed voltage is applied to the input of the actuator drive amplifier section, where it is demodulated (again with quadrature rejection) and changed to a varying d.c. The d-c voltage is converted to an a-c signal output which couples to preamplifier Z200-2, a three-stage, class A amplifier with a grounded emitter output.

The torquer drive amplifier operates a servo valve in the flaperon actuator to furnish necessary aileron control.

Since the pitch servo module and the yaw servo module are identical and interchangeable with the roll servo module, they are not discussed.

Pitch Computer Module

The pitch computer amplifier module accepts inputs from the altitude sensor, Mach sensor, pitch attitude reference, and command coupler normal accelerometer channels. (See fig. 10-17.) The output of the module is applied to the pitch servoamplifier module to command aircraft pitch through stabilizer deflection. The module incorporates a servo channel comprising a motor amplifier and a dual gear ratio servo assembly. The servo consists of a motor tachometer that drives a control transformer and a pitch attitude position-sensing sector switch through a dual-ratio gear train.

The gear ratio is changed through action of a solenoid-operated gear shifter mechanism. In addition, the module incorporates dual-purpose relay circuitry for pitch synchronization monitoring and automatic stabilizer trim functions, ten relays, and a power supply submodule card. The internal constructions and submodule cards of the pitch computer amplifier module are similar to those of the roll computer and roll servoamplifier module.

In the pitch-attitude synchronization mode, relays K4001 and K4006 (fig. 10-17) are deenergized. The control transformer, which is connected back-to-back with the transmitter in the inertial navigation system, senses changes in the pitch attitude of the aircraft. The resulting error signal is fed back to the input of the motor amplifier. The amplified signal drives the motor tachometer, which in turn drives the control transformer through the 1,540:1 gear ratio, thereby maintaining the control transformer output at a null. In order to keep this closed servo loop stable, the output of the tachometer is fed back and summed at the motor amplifier input to provide the necessary damping.

In the attitude hold mode, relay K4001 is energized, hence the motor is clamped. This prevents any further attitude synchronization and establishes a fixed pitch reference. Deviations about this reference attitude are sensed by the control transformer and fed to the AFCS servosystem to perform the necessary corrective action to maintain the reference attitude.

In the altitude and Mach hold mode, relay K4001 is deenergized and K4006 is energized. This allows the servo section to run open loop and act as an electromechanical integrator. The solenoid in the dual-ratio servo assembly is energized, and the gear ratio is changed to 85,900:1. Any altitude or Mach error signal that may exist at the input to the motor amplifier is integrated by driving the control transformer in a direction to reduce the altitude or Mach error to zero, thereby altering the aircraft pitch attitude to maintain the reference altitude or Mach number.

In the pitchback mode, the sector switch assembly, which rotates with the control transformer, establishes the limits of angular pitch displacement from level flight. The limits on attitude hold are +25° (up) and -60° (down) from level flight. When the attitude hold mode is engaged with the pitch attitude in excess of either +25° or -60°, relay K4003 (+25°) or K4004 (-60°) is energized via two conducting segments on the switch assembly. In addition, relay K4006 is energized, thus stopping synchronization; and relay K4001 is deenergized, unclamping the motor input. When either relay

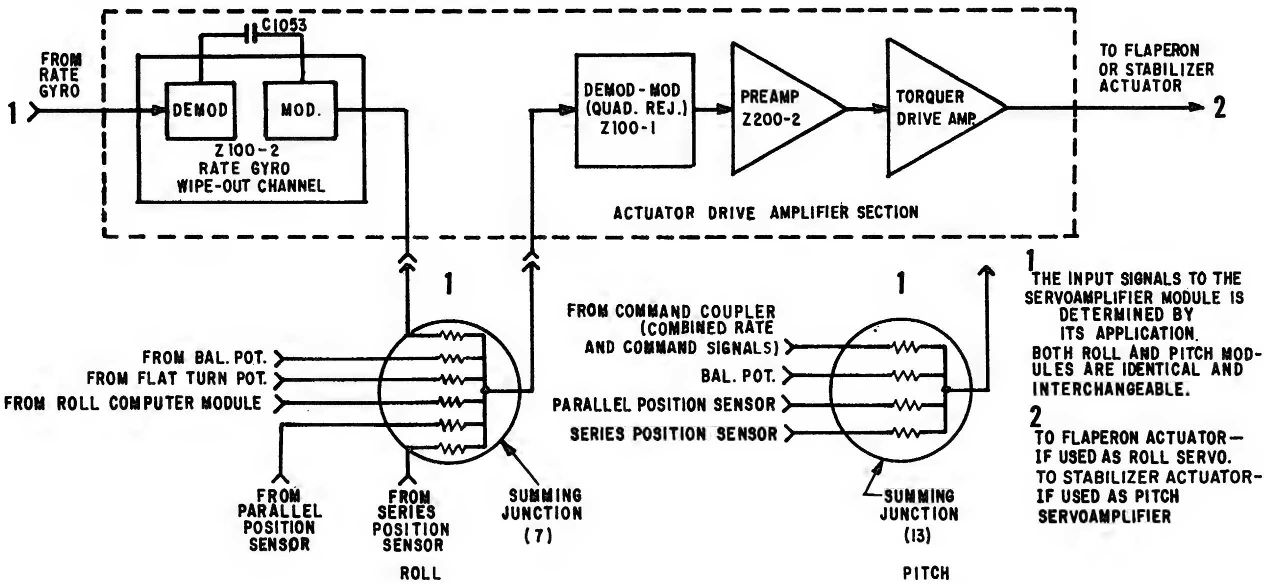

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Figure 10-16.—Roll or pitch servoamplifier module block diagram.

K4003 or K4004 is energized, a fixed voltage is applied to the motor amplifier input from transformer T4001. This voltage causes the motor to run at a rate (predetermined) at which the tachometer output cancels the level voltage input. The resulting control transformer output is fed into the AFCS servosystem that commands the aircraft to pitch back toward either +25° or -60°. The pitch computer motor is clamped and the level voltage removed when the pitch attitude reaches +25° or -60°. This attitude will then be maintained as described above under attitude hold mode operation.

When the return to level switch on the controller is depressed, relay K4003 or K4004 will remain energized (pitch angle less than +25° or -60°) or become energized (pitch angle less than +25° or -60°) through the rack interlocking relays (after completion of roll return to level). The aircraft will pitch back at its established rate until the pitch attitude is +7° (returning from pitchup angle) or 3° (returning from pitchdown angle). The pitchback rate has been set to result in a maximum positive incremental load factor of approximately 3.5 g when pitching back from negative pitch angles and maximum negative incremental load factor of 1 g when pitching back from positive pitch angles.

Heading Computer Module

The heading computer amplifier module (fig. 10-18) accepts signals from the heading attitude reference and from the radio receiver. The output of the heading computer amplifier module, parameter-controlled by a Mach potentiometer, is applied to the lateral path channel of the command coupler to command roll computer shaft position proportional to heading error. Heading corrections are made by commanding aircraft roll through flaperon deflections. The module incorporates a synchronization channel, consisting of a motor amplifier and a servo assembly which follows up the heading data transmitted from the inertial navigation system.

The servo assembly consists of a motor tachometer that drives a control transformer through a reduction gear train. The module also contains heading synchronization monitor circuitry, a power supply, and three relays. In addition, the module provides a 400-Hz a-c signal that is routed through radio receiver relay contacts to drive the heading computer in the TPQ-10 integrator configuration.

The servo section of the heading computer (fig. 10-18) is operative during the following

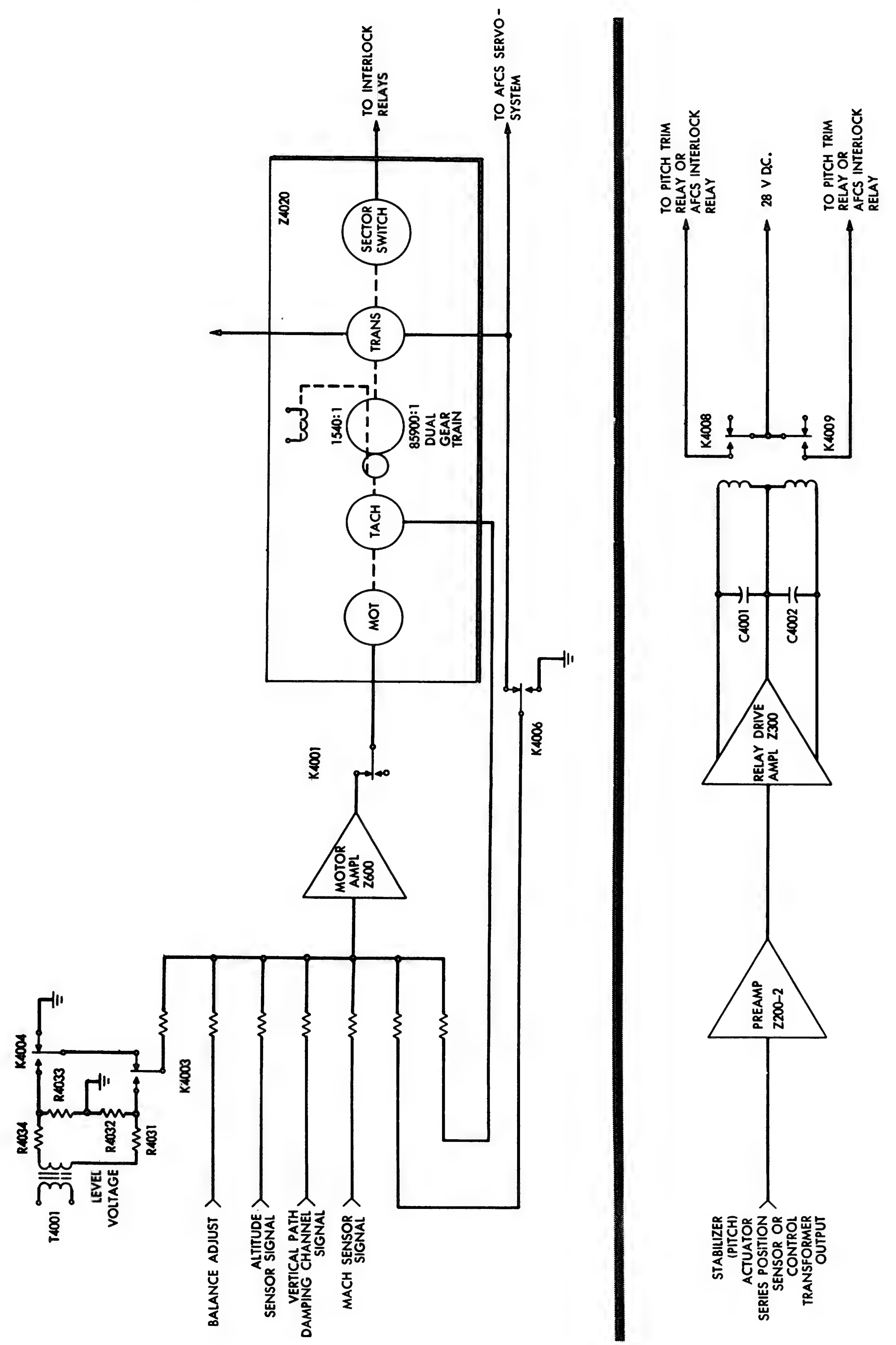

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Figure 10-17.—Pitch computer module block diagram.

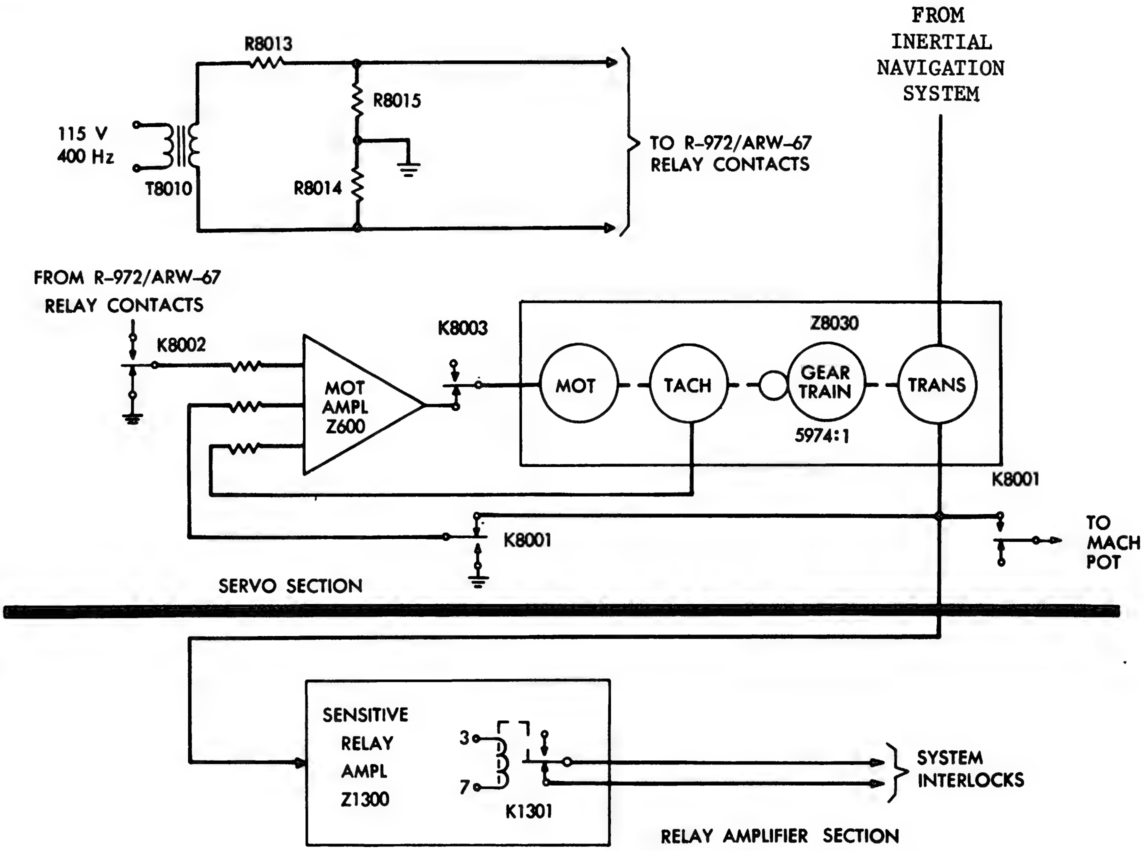

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Figure 10-18.—Heading computer module block diagram.

modes and/or configurations of the AFCS operation; heading synchronization, heading hold, and TPQ-10 mode.

In the heading synchronization mode, relays K8001 and K8003 are deenergized. The control transformer, which is connected back-to-back with the heading transmitter in the inertial navigation system, senses changes in the heading attitude of the aircraft. The resulting error signal is fed back to the input of the motor amplifier. The amplified signal drives the motor tachometer, which in turn drives the control transformer through the 5,974:1 gear ratio, thereby maintaining the control transformer output at a null. To keep this closed servo loop stable, the output of the tachometer is fed back and summed at the motor amplifier input to provide the necessary damping.

In the heading hold mode, relays K8001 and K8003 are energized. Hence, the motor is clamped. This prevents any further heading synchronization and establishes a fixed heading reference. Deviations about this reference are sensed by the control transformer and fed to the AFCS control system through the lateral path channel of the command coupler and of the roll computer, which establishes a bank angle proportional to heading error to perform the necessary corrective action and maintain the heading reference.

In the TPQ-10 mode, relay K8002 is energized and K8003 is deenergized. This allows the servo section to run open loop and act as an electromechanical integrator. Signals (in the form of 400 Hz pulses) received through the AFCS ground control relay are fed to the motor amplifier that drives the control transformer. The control transformer output is fed through the lateral path channel of the command coupler to the roll computer (which functions the same as it does in the heading hold mode) to roll the aircraft, thereby changing heading.

THEORY OF OPERATION

The AFCS is a 400-Hz, information-carrier system with positioning type servosystems. Control and feedback signals are combined by using parallel summation techniques. Parallel summation is accomplished by injecting a-c signals through relatively high impedance resistors to low input impedance transistor summing amplifiers. System gains are established by selecting appropriate summing resistors (the higher the resistor, the lower the gain). Control signal shaping is accomplished by passive RC networks. Prior to shaping, a-c signals are converted to d.c. by transistorized, amplifier-demodulators. The shaped d-c signal is reconverted to a Hz-Hz signal by half-wave modulators for a-c parallel summation. The resulting a-c signal is converted to a proportional mechanical output by the AFCS servosystem. The servosystem output is mechanically summed (in the actuator series configuration) with the manual control system inputs to position the control surface.

NOTE: The air data computer contains six dynamic-pressure q-potentiometers and one Mach-number potentiometer for gain programing. Q-potentiometers No. 1, 2, 5, and 6 are used for parameter control of AFCS g-command, turn coordination, roll rate gyro, and pitchup turn compensation signals, respectively. Q-potentiometers No. 3 and 4, provided for shaping of AFCS yaw and pitch rate gyro signals, are not used in the present AFCS configuration. The MACH number potentiometer is used for shaping of AFCS head-in error signal.

Signal flow theory of operation is developed for each aircraft axis (rudder, flaperon, and stabilizer). The AFCS operation in each axis is divided into operating modes. However, to aid in understanding, the AFCS servosystem and aircraft control system are discussed separately before proceeding with the theory or operation in the operating modes.

A summary of AFCS operation, tying together the AFCS operating modes, switching requirements, and signal data, is presented in table 10-3 following the signal flow discussion.

RUDDER AXIS SIGNAL OPERATION

Two primary control functions are provided by the rudder axis—yaw damper and coordination of turn maneuvers. The selection of these functions is obtained by engagement of the ON-OFF switch on the controller.

A diagram illustrating rudder axis signal flow is shown on figure 10-19. The combined servo and control system is a surface positioning device where sensor and control inputs are summed at summing point (2) of the figure to command surface position.

The rudder AFCS servosystem consists of the actuator drive amplifier section of the yaw servoamplifier and the AFCS portion of the rudder electrohydraulic actuator, as shown in figure 10-19. The actuator drive amplifier rejects quadrature voltages and amplifies and converts input a-c control signals to d-c signals. The d-c output polarity is dependent upon the input signal phase relationship. The actuator drive amplifier d-c output is fed to the actuator electrohydraulic servo valve. The valve commands actuator mechanical output at an initial rate, and in a direction dependent on the polarity of the d-c signal input. The actuator position sensor develops an a-c signal proportional to actuator mechanical output. This position feedback signal closes the AFCS servosystem loop (summing junction (2)), providing rudder actuator or position proportional to the a-c signal input. When the position sensor output cancels the net input to summing junction (2), thereby reducing the actuator drive output to zero volts d.c., the actuator stops moving. Balance potentiometer R1072Y is summed with the feedback signal. This potentiometer is required to remove electrical and mechanical imbalances and thereby eliminate engage errors.

The AFCS output and the manual rudder-pedal input are mechanically summed in a series arrangement (summing junction (3)). This series arrangement prevents surface deflections due to AFCS electrical inputs being reflected at the rudder pedals. Both electrical and manual inputs can be injected simultaneously, with the resultant surface deflection being the sum of the two. The mechanical summation of the two inputs is fed through the control linkages to the power actuator. The rudder actuator does not operate in parallel; it is capable of manual and series operation only. The series mode is the AFCS operating mode of the actuator.

NOTE: When an actuator operates in series, the applicable aircraft control surface is positioned through its electrohydraulic actuator so that no motion is transmitted back to the stick. Only the stabilizer actuator has a parallel

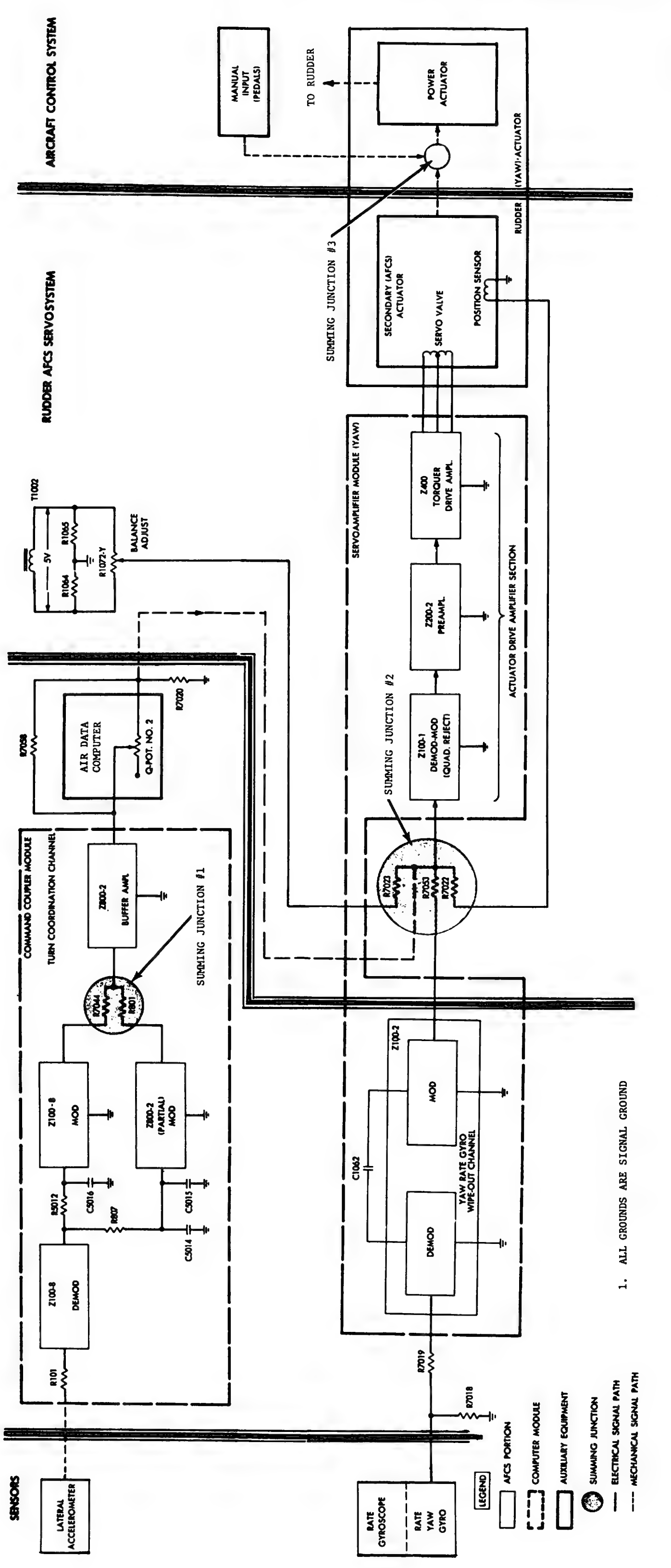

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Figure 10-19.—Rudder axis signal flow diagram.

operating mode. In this configuration, aircraft stabilizer motion is transmitted through mechanical linkage to the stick. The stabilizer actuator operates in the parallel configuration during the g-command mode of AFCS operation.

The AFCS can command up to ±4° of rudder surface movement through the power actuator. The rudder pedal is mechanically limited to command ±35° with flaps or gear down (landing condition). In the clean configuration (flaps and gear up), the rudder pedals can command ±4°.

The rudder axis functions identically in all modes to provide yaw damping and turn coordination.

Stability augmentation mode engagement energizes the actuator solenoid valve to permit hydraulic flow, and releases the mechanical lock on the rudder actuator, allowing automatic rudder control to provide yaw damping and coordination of turn maneuvers.

Yaw Damper

The yaw damper function provides a rudder deflection proportional to and opposing aircraft angular yaw rate. The stability sensor for the yaw damper is the yaw rate gyro portion of the rate gyroscope. The sensor output is shaped in the yaw rate gyro wipe-out channel before being inserted into the rudder AFCS servosystem (input summing junction (2), fig. 10-19). The wipe-out channel is a high pass filter that eliminates yaw damper opposition to sustained manual and automatic turn commands. The wipe-out is accomplished by converting the sensor a-c signal to a d-c signal in the demodulator section of demodulator-modulator Z100-2 and applying it to a 2-second RC lead network. The signal is reconverted to 400 Hz in the modulator portion of Z100-2 for parallel summation with other inputs to the AFCS servosystem.

Turn Coordination

Turn coordination functions to provide rudder control proportional to aircraft side accelerations (accelerations along either wing). Side accelerations can occur in straight-and-level flight (from directional axis mistrim) or in turns (from the aircraft turn coordination requirements). An a-c signal, proportionate to aircraft side acceleration, is derived from the center-of-gravity-mounted lateral accelerometer. This signal is fed to the rudder AFCS servosystem via the turn coordination channel of the command coupler module. This channel is divided into two signal path sections—one section for displacement control and the other for integral control. The displacement control commands rudder position proportional to side acceleration but, this alone could not satisfy steady-state coordination control requirements without affecting the short-period stability. Therefore, the displacement gain is augmented by the integral control to satisfy the maneuvering coordination requirements with minimum effect on the short-period response.

The turn coordination channel uses demodulator Z100-8 (fig. 10-19) to convert the lateral accelerometer a-c signals to d-c signals prior to sectionalizing the signals. The displacement section filters this d-c signal with a passive RC network (0.1-second time constant) to remove signal noise and modulates it at Z100-8 to 400 Hz for summation with the integral section output at buffer amplifier Z800-2 (summing junction (1)). The integral section heavily filters the d-c signal with an RC lag network (30-second time constant) and modulates it at Z800-2 to 400 Hz for summation with the displacement signal at summing junction (1). The combined coordination signal is amplified at Z800-2, shaped, fed through amplified data computer dynamic-pressure control, and summed with the wiped-out yaw rate gyro signal at the input to the AFCS servosystem (summing junction (2)). The air data computer parameter control is a 50,000-ohm potentiometer in which the resistance increases linearly with dynamic pressure (q). The low-dynamic-pressure end of the potentiometer (zero-resistance) is tied to signal ground through resistor R7020 and is tied to the potentiometer arm through resistor R7058. The values of resistors R7020 and R7058 may be varied to shape the control gain parameter as required. The control gain that results is inversely proportional to dynamic pressure.

FLAPERON AXIS SIGNAL OPERATION

Eight primary functions are provided by the flaperon axis as follows:

1. Roll damper.
2. Roll attitude synchronization.
3. Roll attitude hold.
4. Heading hold.
5. TPQ-10 commands.

6. Ballistic computer set roll commands.
7. Return to level.
8. Control stick steering.

The selection of these functions is governed by the switches on the controller, the TQP-10 engage switch on the ground controlled bombing system panel, or by the application of manual forces to the aircraft control stick. The flaperon axis signal flow diagram (fig. 10-20) presents signal flow from sensors to the flaperon control surface. The combined servo and control system is a surface-positioning device where sensor and control inputs to summing junction (7) command surface position.

The flaperon servosystem AFCS functions similar to the rudder AFCS servosystem in that electrical inputs (summing junction (7), fig. 10-20) result in actuator displacement. However, the flaperon servosystem is physically different from the rudder servosystem. There are two identical power actuators associated with the flaperon control system—one to power each set of flaperons, and an autopilot actuator which drives the flaperon power actuators. The autopilot actuator is only capable of manual and series operation.

The flaperon power actuators operate with mechanical feedback so that AFCS or manual inputs result in a proportional actuator displacement. The control linkage between the autopilot actuator and the power actuators restricts operation of the power actuators so that AFCS or manual stick inputs deflect only one set of flaperons (right or left) at any one time. The phase of the AFCS electrical input signal determines which flaperon power actuator operates.

Unlike the rudder system, the manual stick input is applied through the position sensor within the actuator. The relative position of the stick and the sensor (summing junction (8)) generates an electrical signal which is algebraically added to AFCS inputs at the servo-amplifier (summing junction (7)). The AFCS flaperon travel limit (±12.5° about the engaged position) is established by the flaperon limiter Z1400. If the surface authority limit is exceeded (due to a malfunction of the series mode limiter Z1400), one of the two autopilot actuator flaperon authority limit switches is actuated. The contacts of these switches are located in series with the holding solenoid of the ON-OFF switch. Actuation of either flaperon authority limit switches will cause the ON-OFF switch to drop out to the OFF position, thereby disengaging all automatic control.

The flaperon servosystem balance potentiometer (R1073R) signal is adjusted to compensate for the electrical and mechanical imbalances at initial system installation and during specified maintenance procedures. This phase-reversible signal is injected at summing junction (7).

Stability Augmentation Mode

Stability augmentation mode engagement releases the series link lock on the autopilot actuator, allowing series type automatic flaperon axis control to provide roll damping. Roll attitude and heading synchronization operate to automatically synchronize the flaperon axis to the roll attitude and heading of the aircraft during the stability augmentation mode and prior to the attitude hold mode.

ROLL DAMPER.—The roll damper function provides a flaperon deflection (rolling moment) proportional to and opposing aircraft angular roll rate. The stability sensor for the roll damper is the roll rate gyro (fig. 10-20). The sensor output is parameter controlled, shaped in the roll rate gyro wipe-out channel, and then limited before being inserted into the flaperon AFCS servosystem (input summing junction (7)). The sensor signal is fed through the air data computer dynamic-pressure control. The operation of the air data computer parameter control was previously discussed.

The parameter-controlled roll rate signal is applied through easy engage circuit Z1090 to the wipe-out channel. The easy engage circuit removes the roll damper signal when the control stick is moved laterally out-of-detent. When the control stick is returned to lateral detent, the roll damper signal is reapplied smoothly to the desired level through the easy engage circuit.

The wipe-out channel is a high pass filter that eliminates roll damper opposition to sustained bank commands (manual and automatic). The wipe-out is accomplished by converting the sensor a-c signal to a d-c signal in the demodulator section of demodulator-modulator Z100-2 and applying it to a 2-second RC lead network. The signal is reconverted to 400 Hz in the modulator portion of Z100-2 for parallel summation with other inputs to amplifier-limiter Z1400 (summing junction (6)). The shaped roll rate signal is amplified and limited by amplifier-limiter Z1400 and parallel summed

with other inputs (summing junction (7)) to the AFCS servosystem. The limiter portion of Z1400 limits the AFCS servo input to the actuator drive amplifier so that the flaperon surface deflection does not exceed the established flaperon limits.

ROLL ATTITUDE SYNCHRONIZATION.—The roll attitude reference for the AFCS is obtained from the back-to-back coupling of the inertial navigation system roll attitude transmitter to the roll computer control transformer. The roll computer amplifier module (consisting of an electromechanical servo assembly that drives the roll control transformer, an electrical sine-cosine resolver, and roll attitude sector switches) provides continuous roll attitude synchronization prior to and during the stability augmentation mode. The control transformer senses changes in the aircraft roll attitude and develops a proportional error signal.

This signal is fed to the roll computer motor amplifier input (summing junction (5)) via deenergized relays K3003 and K3004. The output of the motor amplifier drives the roll computer servo assembly until the control transformer output is nulled. A portion of the servo assembly tachometer signal, whose output voltage is proportional to motor speed, is parallel summed with the control transformer input to damp the servo loop. The roll computer servo assembly is alined so that its shaft position (relative to the inertial navigation system resolver) and its sector switch orientation correspond directly to aircraft roll attitude from level flight.

HEADING SYNCHRONIZATION.—The heading reference for the AFCS is obtained from the back-to-back coupling of the inertial navigation system heading reference transmitter to the AFCS heading computer control transformer. The heading computer amplifier (an electromechanical servo assembly which drives the heading control transformer) provides continuous heading synchronization prior to and during the stability augmentation mode. (Heading synchronization is accomplished in all operating modes of the AFCS except heading hold and TPQ-10.)

The control transformer senses changes in aircraft heading and develops a proportional error signal. This signal is fed to the heading computer motor amplifier input (summing junction (15)) via unenergized relay K8001. The output of the motor amplifier drives the heading computer servo assembly until the control transformer output is nulled. The heading computer servo assembly shaft position, therefore, corresponds directly to aircraft heading.

The heading synchronization function is monitored continuously and automatically within the heading computer. The control transformer output is coupled to the heading computer relay amplifier (Z1300) which is calibrated to energize its output relay (K1301) whenever the heading synchronization error exceeds ±2°. Contacts of relay K1301 are included in the interlock string to the AUTO STAB-AUG switch. These contacts of synchronization monitor relay K1301 are bypassed when the attitude hold mode is engaged.

Attitude Hold Mode

Selection of the attitude hold mode via the controller AUTO STAB-AUG switch provides roll attitude hold or heading hold in addition to roll damping. The roll damper function for the stability augmentation mode is identical to the attitude hold mode. Roll attitude synchronization is stopped, and the roll computer control transformer error signals are applied to the AFCS servosystem. The roll attitude existing at the time of attitude hold mode engagement determines the nature of the flaperon control function of the AFCS. These functions are either roll attitude hold or heading hold.

ROLL ATTITUDE HOLD.—The roll attitude hold configuration is engaged when the attitude hold mode is selected and the aircraft roll attitude is greater than 5° and less than 60°. Aircraft roll attitude displacement and rate deviations are sensed and used to proportionately position the flaperons to maintain the reference (engaged) aircraft attitude. Engaging the AUTO STAB-AUG switch on the controller stops aircraft attitude synchronization and clamps the roll computer (provided the existing aircraft attitude is greater than 5° and less than 60° as sensed by the roll computer position sector switches). This clamped computer position establishes the reference roll attitude. Deviations from this attitude are sensed by the locked roll computer control transformer. Hence, the inertial navigation system roll attitude transmitter detects any aircraft roll attitude change, which is then transformed to a proportional a-c signal by the control transformer. This roll attitude deviation signal is fed through energized relay K1010 to the input of the amplifier-limiter Z1400 (summing junction (6)), where it is amplified and limited. (See

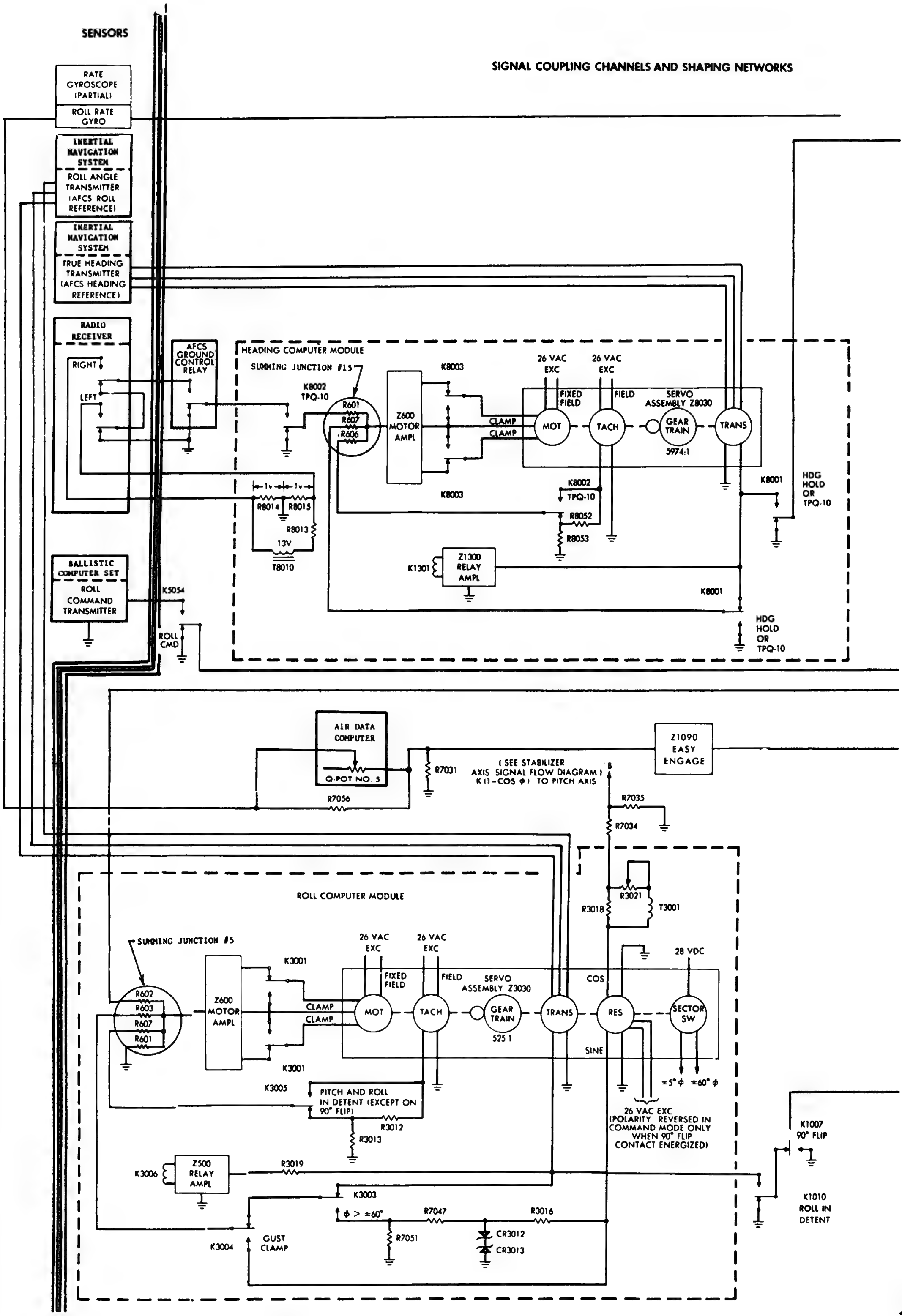

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Figure 10-20.—Flaperon axis signal flow diagram.

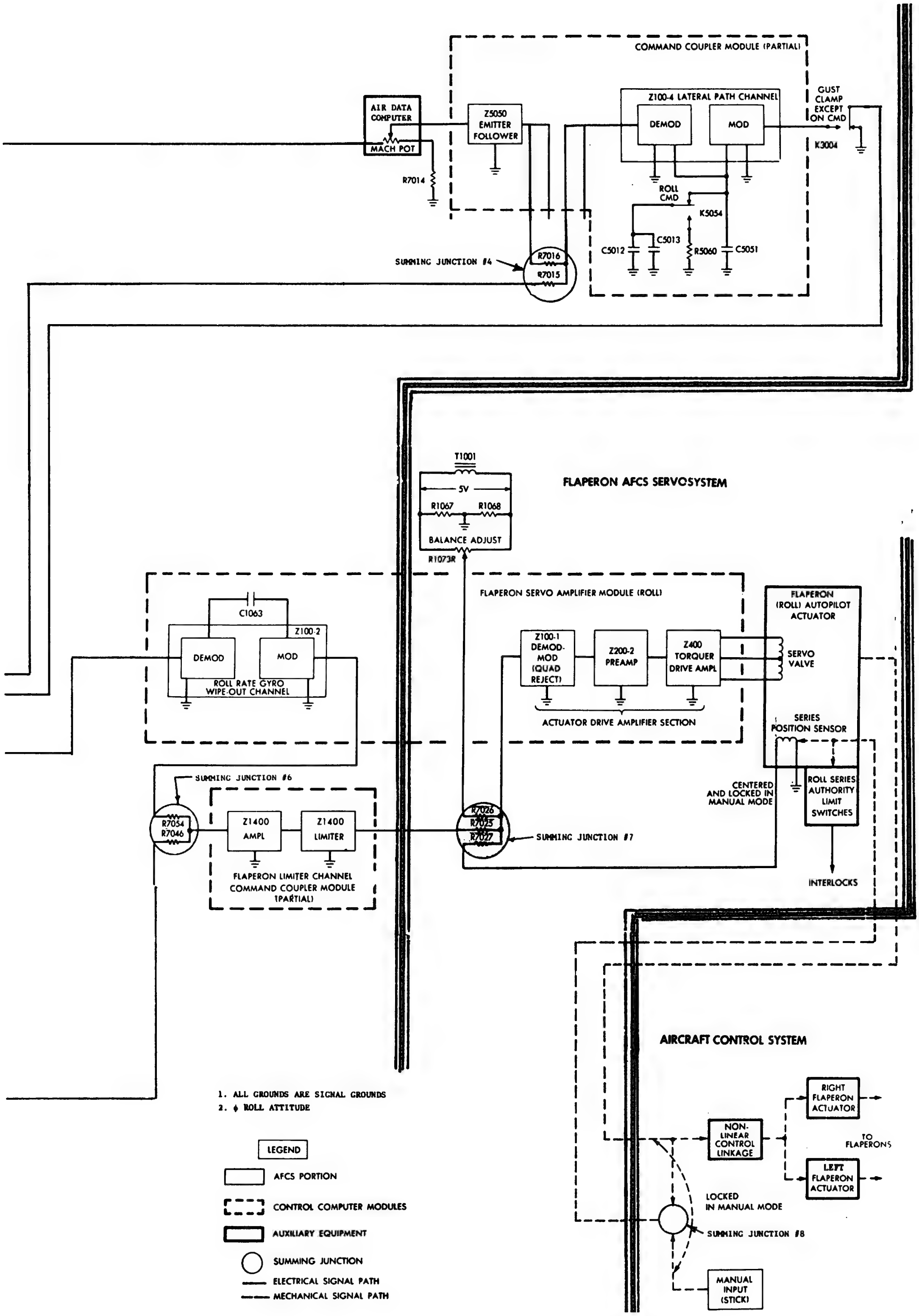

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Figure 10-20.—Flaperon axis signal flow diagram—Continued.

figure 10-20.) The output from Z1400 is then fed to the flaperon AFCS servosystem (summing junction (7)) and commands flaperon deflection in a sense to maintain the reference attitude.

The use of a relatively high attitude gain, required to maintain tight attitude control, dictates the need for aircraft attitude rate information for mode stabilization. Therefore, signals proportional to roll rate, derived from the roll rate gyro, are summed with the control transformer attitude signals (summing junction (6)) to provide the phase lead required for stable system operation. The roll rate gyro signal is parameter controlled and then shaped in the roll rate gyro wipe-out channel ahead of the amplifier-limiter input summing point to eliminate opposition to sustained roll rate commands. The wipe-out circuitry (high pass filter) is identical to that used in the rudder axis.

The upper limit on roll attitude hold is 60° either side of level flight. If the aircraft attitude is greater than 60° when the attitude hold mode is selected, the AFCS will roll the aircraft automatically back to, and hold, 60° roll attitude. Attitude synchronization is continuous for all aircraft attitudes, thereby alining the roll computer shaft to the actual aircraft attitude. The roll computer resolver is connected directly to the electromechanical servo assembly shaft in a manner to produce an output from the sine winding that is a measure of shaft rotation and hence to roll attitude displacements from zero roll attitude (wings level).

If the aircraft attitude is greater than 60° when the attitude hold mode is selected, attitude synchronization stops and the roll computer remains unclamped because of the interlocks associated with the roll computer attitude sector switches. The resolver sine output is inserted into the roll computer (summing junction (5)) in place of the control transformer signal (relay K3003 is energized) and is summed with the full tachometer output (relay K3005 is energized). (See fig. 10-20.) Zener diodes CR3012 and CR3013 are used to limit the resolver sine signal to a value approximately equivalent to the resolver output at 45° of roll. The divided sine signal, in conjunction with the full tachometer feedback, establishes the computer motor rollback rate in a direction dependent on resolver signal phase. As the motor is driven, the control transformer develops an output signal to command flaperon deflection (via energized relay K1010 and the servosystem) which rolls the aircraft back toward 60°. The roll computer is clamped by action of the attitude sector switch interlocks when a roll computer shaft position of 60° is achieved. The aircraft continues to roll until its attitude becomes 60° and the control transformer output is nulled. This attitude is maintained in the same manner as that previously described for roll attitude hold.

HEADING HOLD.—The selection of the attitude hold mode with the aircraft roll attitude, right or left, between 0° and 5° results in automatic wing leveling and heading hold engagement. Heading hold is accomplished by commanding bank angle proportional to deviations in aircraft heading from the reference. The roll computer attitude sector switch detects the aircraft roll attitude between 0° and 5° and supplies excitation continuity to interlock relays. Contacts of these relays open the roll computer motor clamp circuitry, insert the roll computer sine output to the input of the motor amplifier, energize the heading computer clamping circuit, and select the clamped heading computer control transformer heading error signal.

The roll computer is driven by the unlimited sine resolver output in a direction to reduce its output to zero, which corresponds to 0° of roll attitude. The roll computer control transformer produces the command input to the AFCS servosystem to provide proportional flaperon deflection for wing leveling. As the wings level, heading error signals, derived from the heading computer control transformer, are fed to the input of the roll computer (summing junctions (5)) via the air data computer Mach potentiometer and the command coupler lateral path channel. This input drives the roll computer servo assembly until the sine resolver output cancels the heading input. The angle through which the roll computer servo assembly shaft (and, therefore, the control transformer) rotates is directly proportional to heading error.

The aircraft (and the inertial navigation system roll transmitter) rolls in response to the control transformer error to reduce the error to zero. The resulting bank angle is in a direction to reduce the heading error. Since the established bank angle is proportional to heading error, the bank angle is reduced as the heading error is decreased to zero until a wings-level condition is established at the reference heading.

The lateral path channel in the heading loop provides heading error signal filtering and limiting. The heading signal error a.c. is

injected at summing junction (4), converted to d.c. by the standard demodulator (part of Z100-4), filtered with an RC lag network having a 2-second time constant, and modulated to 400 Hz for signal summation at the input to the roll computer (summing junction (5)). (See fig. 10-20.) The maximum output of the modulator (part of Z100-4) is established by its excitation voltage. In this application, full output of this modulator (lateral path channel) is equivalent to 30° of bank. Lateral path channel input command authority is thereby limited to a maximum of 30° of bank. A Mach potentiometer and an emitter-follower (Z5050) are located between the heading error output and the lateral path channel input. The Mach potentiometer, located in the air data computer, continuously adjusts the heading gain as a function of aircraft Mach number to obtain constant dynamic response over the airspeed range. It provides an approximate three-to-one decrease in heading gain from aircraft maximum airspeed to the landing condition. The emitter-follower (Z5050) provides an impedance match between the Mach number potentiometer and the lateral path channel input, thus allowing the heading gain to be a linear function of Mach number.

Altitude and Mach Hold Mode

The altitude and Mach hold function is a longitudinal control function (stabilizer axis). The flaperon control axis functions independently of the altitude and Mach hold control. The lateral mode (attitude hold or heading hold) existing at the time of altitude and Mach hold engagement is retained.

TPQ-10 MODE

The TPQ-10 mode provides a ground controlled vectoring (or steering) capability for close support bombing attack. The system includes a ground radar, a ground computer, ground data link transmitter, radio receiver, and an airborne X-band beacon (for low-angle and long-range tracking). During TPQ-10 mode control, the aircraft (tracked by radar) is always under ground command, which may require a direct run to target or commanded loiter. Input information to the AFCS consists of the closure of one of two sets of relay contacts of the radio receiver. One set of relay contacts commands correction to the left; the other set commands correction to the right. Closure of either relay is intended to command a correction of 3° of heading for each second of closure time. Relay closure signals, when required, are transmitted at a rate of 1 per second.

Selection of the TPQ-10 mode is accomplished by the pilot, using the TPQ-10 engage switch (solenoid-held toggle switch) on the ground controlled bombing system (GCBS) control panel. In order to engage the TPQ-10 mode of operation, the AFCS must be in the attitude (heading) hold mode or command mode, with the aircraft bank angle less than 5°. Selecting the TPQ-10 mode while in command mode drops out the command (CMD) switch, thus disengaging the command mode. If the aircraft bank angle is greater than 5°, the TPQ-10 engage switch will not hold in and the roll attitude hold mode will be retained.

When the appropriate conditions are met and the TPQ-10 mode is engaged, relays K8001 and K8002 are energized. These relays unclamp the heading computer, switch the heading computer control transformer heading error signal to the air data computer Mach potentiometer, and convert the heading computer to an electromechanical integrator (by removing the heading control transformer feedback loop and selecting maximum tachometer output). The radio receiver output signal is inserted into the heading computer (summing junction (15)), through the TPQ-10 AFCS/ground control. (The relay prevents interaction between other TPQ-10 ground stations transmitting to other aircraft at the same carrier frequency but different code, and is energized by a radio receiver coding section in conjunction with the pilot's manual selection of the proper code.)

Out-of-phase and in-phase 400-Hz excitation voltages to the radio receiver left-right relays are supplied by transformer T8010, located in the heading computer. A ground command to change heading results in the closure of one of the radio receiver relays for a length of time determined by the ground based computer. Integration of the signal input pulse is performed by the heading computer at a rate of 3° of heading computer shaft rotation per second. The heading computer control transformer is thereby rotated, producing a heading error signal which is fed to the input of the roll computer (summing junction (5)) via the air data computer Mach potentiometer and the command coupler lateral path channel. Continual heading corrections may be applied to the aircraft by ground transmitted signals,

resulting in radio receiver output pulses of 1/30 to 1-second duration, corresponding to 0.1° to 3° of heading change at a rate of 1 pulse per second.

Command Mode

Selection and engagement of the command mode disables roll attitude synchronization and applies roll computer transformer error signals to the AFCS servosystem. Three lateral command mode control phases are provided in the AFCS: a roll command phase, a return to level phase, and an automatic landing system (ALS) data link command phase. The CMD solenoid-held toggle switch on the AFCS controller selects the command mode. Selection of the roll command return to level or ALS data link command phase is accomplished by energizing the appropriate AFCS interlock circuits with 28-volt d-c interlock signals generated by the ballistic computer. Generally, when the command mode is selected, the roll command phase is assumed. The AFCS operates in the roll command phase until a signal (28 volts d.c.) is fed to the AFCS from the ballistic computer. The AFCS interlocks use this 28-volt d-c signal to establish the return to level or ALS data link phase. The following discussion presents the AFCS command mode implementation by phase.

ROLL COMMAND PHASE.—To establish the roll command phase, the AFCS must be in the attitude hold mode (or a higher mode) prior to engaging the CMD switch on the controller. Engagement of the CMD switch with the AFCS in the TPQ-10 mode of operation drops out the TPQ-10 engage switch and results in disengagement of the TPQ-10 mode. Also, a 28-volt d-c roll-command-available signal from the ballistic computer must be present in order to latch the CMD switch. When the roll command phase is engaged, relay K5054 (fig. 10-20) is energized, switching the roll command transmitter output into the lateral path channel input through resistor R7015. At this point, the AFCS functions in the same manner as the heading hold mode, except that the lateral path channel filter time constant is changed from 2 seconds to 0.06 second, the Mach number potentiometer is bypassed and the heading computer synchronizes aircraft heading. The difference between aircraft heading and desired heading is computed by the ballistic computer and inserted into the AFCS as a roll command. This input drives the roll computer servo assembly until the sine resolver output cancels the roll command. As stated in the heading hold discussion, AFCS bank commands are limited to a maximum of 30° by the lateral path channel output voltage limit. The ballistic computer-commanded maneuvers may consist only of relatively simple roll commands to guide the aircraft to its target, or they may take the form of complex operations such as a LAB (low altitude bombing) maneuver. The discussion thus far pertains to the relatively simple roll command maneuver.

If a LAB maneuver is involved, then the following discussion is applicable. The LAB maneuver requires ballistic computer sequential control of both lateral and longitudinal aircraft axes to pitch the aircraft up and over longitudinally and to return it to a wings-level condition laterally. The flaperon axis return to level phase rolls the aircraft back to within 5° of wings-level attitude and then initiates the pitch-level phase (in the stabilizer axis) to return the aircraft to a pitch-level condition.

The LAB sequence of operations starts with the AFCS in the command mode. Ballistic computer control signals in the lateral path channel guide the aircraft to its target. Stabilizer axis control in the form of g-commands (also from the ballistic computer) is active. At the proper time (determined by the ballistic computer), the aircraft is commanded to start its up-and-over maneuver. As the aircraft reaches an elevation angle of 90°, inertial navigation system slew is initiated and the 90° flip sensor on the INS attitude reference sends a 28-volt d-c signal to the AFCS. This interlock signal energizes relay K1007 (fig. 10-20), removing roll computer control transformer error signals from the AFCS servosystem. Relay K3004 is also deenergized, simultaneously removing lateral path channel inputs from the roll computer and reverting the roll computer to its roll attitude synchronization configuration to aline it to the slewed INS reference.

At the same time, the excitation to the electrical resolver is reversed so that its phase is correct for inverted flight. When the roll computer has alined itself to within 2° of the INS reference, the 90° flip relay K1007 is deenergized, restoring roll computer control transformer error signals to the AFCS servosystem. Also, relay K3004 is reenergized, thus reverting ballistic computer control to the roll

axis. The excitation phase reversal to the electrical resolver remains. The aircraft continues along the flightpath computed by the ballistic computer and in an inverted attitude. When the aircraft attitude is within 5° of elevation angle, the ballistic computer removes the g-command longitudinal input. In order to complete the LAB maneuver, the aircraft must be rolled back to a straight and level attitude. Therefore, immediately after the ballistic computer g-command is removed from the AFCS, the ballistic computer generates a 28-volt d-c interlock signal pulse to initiate the return to level phase.

RETURN TO LEVEL PHASE.—When the aircraft is in position to return to level (as determined by the ballistic computer), a 28-volt d-c signal pulse is fed from the ballistic computer to the AFCS interlock system that establishes the return to level phase. In the flaperon axis, this 28-volt d-c signal is used to energize relay K3003 and to deenergize relays K3004 and K5054. (See fig. 10-20.) Thus, when the roll computer is switched to the return to level configuration, the aircraft rolls back to its normal flight attitude reference. Relays K3003 and K3004 complete the roll computer loop around the electrical sine resolver through the roll rate limiter composed of diodes CR3012 and CR3013 and resistor R3016. The limited resolver sine output is inserted into the roll computer (summing junction (5)) and is summed with the full tachometer output. The algebraic sum of the two signals establishes the computer motor roll-back rate. The direction of motor rotation depends on the initial resolver output phase. As the motor is driven, the control transformer develops an output signal to command flaperon deflection via the AFCS servosystem. The aircraft rolls in response to the control transformer signals so that the control transformer output is nulled. Relay K5054 removes the ballistic computer roll commands from the input of the lateral path channel. The roll computer sector switch detects when the aircraft has rolled back to 5° and supplies excitation continuity to the interlock relays. Contacts of these relays bypass the roll limiter in the roll computer and inserts the ballistic computer roll commands through the lateral path channel into the roll computer. The lateral axis configuration reverts to its initial condition, that is, the roll command phase.

ALS DATA LINK PHASE.—The ALS data link phase is established in a manner identical to that used to establish the roll command phase. The essential difference between the two is in the AFCS interlocking circuits. When the roll command phase is operative, the pilot may assume manual control on the aircraft (if he so desires) by inserting commands through the stick without the necessity of reengaging the CMD switch on the controller at the conclusion of manual control inputs. The AFCS interlocking circuits prevent this from being done in the ALS data link phase. Hence, it is then necessary for the pilot to reengage the CMD switch and thus reassume the ALS data link phase.

The ALS automatically tracks approaching aircraft with radar. The instantaneous position coordinates of the aircraft are supplied by the radar to a carrier-based flightpath computer that compares actual flightpath to a desired flightpath. Control signals are transmitted by radio to the aircraft for both lateral and longitudinal corrections as a function of the error between actual and desired flightpath. This radio information is converted to electrical error signals in the ALS data link (decoder-encoder) in the aircraft to supply command signals to the AFCS. Lateral control signals are applied to the lateral path channel. Longitudinal control signals are applied to the altitude, Mach, and pitch command channel. Ballistic computer 28-volt d-c interlock signals, fed to the AFCS interlocks, set up the appropriate signal flow configurations to maintain control throughout the ALS approach and landing operation. Lateral axis control is identical to that used in the roll command phase.

Return-to-Level Mode

The return-to-level mode is selected by engaging the return-to-level pushbutton switch on the controller. In order to establish the return-to-level mode, the AFCS must be in the attitude hold, heading hold, TPQ-10, altitude hold, or Mach hold mode prior to engaging the return-to-level switch. With the AFCS in the TPQ-10 mode, engagement of the return-to-level mode disengages the TPQ-10 mode and provides heading computer synchronization on aircraft heading. In the heading hold mode, engagement of the return-to-level mode unclamps the heading computer and also results in the heading synchronization configuration. Roll attitude synchronization is disabled and roll computer

control transformer error signals are applied to the AFCS servosystem. Two return-to-level phases are provided in the AFCS—a roll-level phase and pitch-level phase.

Starting from any roll attitude, the roll return to level function automatically rolls the aircraft to a wings-level condition and concludes the operation by putting the AFCS flaperon axis control in the heading hold mode.

Control Stick Steering Mode

The AFCS is implemented for control stick steering; that is, pilot-applied stick force causes the system to revert to the stability augmentation mode while the aircraft is maneuvered manually. With the attitude hold mode engaged, application of lateral stick force (1.4 lb) sufficient to actuate the force-sensitive switches in the stick removes the roll attitude reference and the roll rate damper from the system (deenergizes relay K1010), and the roll and heading computers revert to the synchronization mode. Continued force results in a manual input to the flaperon control system (summing junction (8)) producing flaperon deflection and an aircraft roll rate. While the stick force is applied, the AUTO STAB-AUG switch on the controller remains engaged, and the AFCS provides yaw and pitch damper control. The roll damper function is deactivated by the easy engage circuit Z1090 to eliminate damper resistance to the commanded roll rate. Also, the roll damper signal is reapplied smoothly through the easy engage circuit Z1090. The easy engage circuit Z1090 allows the roll rate signal to increase to the desired level with a time constant of 0.32 second. In the flaperon axis, the manually commanded roll attitude is continuously synchronized (as in heading) as described previously. If attitude hold or the command mode had been selected prior to the application of lateral stick force, their respective engage switches would not disengage with stick force application. Upon release of the stick, the attitude hold or command mode is automatically reengaged and normal operation of the particular control mode is resumed (except for the data link phase). If lateral stick force is applied while in the TPQ-10 mode, the TPQ-10 engage switch will drop out, thereby disengaging the TPQ-10 mode. Subsequent release of the stick reestablishes the attitude hold mode.

STABILIZER AXIS SIGNAL OPERATION

Nine primary functions are provided by the stabilizer axis as follows:

1. Pitch damper.
2. Pitch attitude synchronization.
3. Pitch attitude hold.
4. Automatic pitch trim.
5. Attitude hold.
6. Mach hold.
7. Command mode.
8. Return to level.
9. Control stick steering.

NOTE: A general description of the command and return to level modes was given in the flaperon axis discussion and is not repeated in this section.

The selection of the stabilizer functions is controlled by the switches on the controller or the application of manual forces to the aircraft control stick. The stabilizer axis signal flow diagram (fig. 10-21) presents stabilizer signal flow from the sensors to the stabilizer control surface.

As in the other axes, the combined servo- and control system is a surface-positioning device where sensor inputs to summing junction (13) command position of the control surface.

The stabilizer axis servosystem functions similar to the rudder and flaperon AFCS servosystems in that electrical inputs (summing junction (13)) result in stabilizer displacement. However, the stabilizer servosystem is physically different from either the rudder or the flaperon servosystem. The single stabilizer electrohydraulic actuator is capable of manual, series, or parallel operation. The series and parallel modes are the AFCS operating modes of the actuator.

In the series mode, the power actuator operates with mechanical feedback so that electrical or manual inputs result in a proportional actuator (and surface) displacement. In this configuration, stabilizer actuator electrical inputs deflect the stabilizer control surface without moving the control column. Similar to the rudder axis, the stabilizer series mode mechanically sums the manual and electrical inputs to the power actuator (summing junction (14)) and has an electrical control surface authority limit (1.2°) about the engaged position. The manual surface authority is mechanically limited to

command 2° up, 10.75° down in the clean condition (flaps and gear up), and 2° up, 23.75° down in the landing condition (flaps or gear down).

The parallel mode is assumed when a 28-volt d-c solenoid, internal to the actuator, is energized. This action converts the actuator to the parallel mode configuration and allows electrical inputs to control the stabilizer position. Energizing this solenoid activates a hydraulic clamp that centers and locks the manual input linkage to actuator output and removes the mechanical feedback from around the power actuator. In this configuration, manual inputs can only be inserted by overriding the manual lockout device. Electrical inputs are fed, via the AFCS, to the actuator. The hydraulic clamp deactivates the series sensor. In order to restore the combined servo and control system to a positioning type system, the parallel position sensor is clutched into the servo loop and provides an a-c signal proportional to stabilizer position.

This a-c signal is fed back to the AFCS servosystem input (summing junction (13)). The clutched surface position transducer supplies an output only in the parallel mode configuration. The transducer clutch and the actuator parallel mode solenoid are energized simultaneously by the AFCS interlock system in the g-command or pitch-command phase of the command mode or when the return to level mode is selected. Control signal inputs to the stabilizer AFCS servosystem (summing junction (13)) are canceled by the transducer as the surface is deflected proportionately. In this mode, the manual control column is connected directly to the surface, and surface deflections resulting from electrical control signals move the control column proportionally.

The stabilizer servosystem has a balance potentiometer (R1071P) similar to that used for the other axes. It is adjusted at initial system installation and at subsequent specified maintenance operations to compensate for electrical and mechanical imbalances. This signal is injected at summing junction (13).

Stability Augmentation Mode

Stability augmentation mode engagement energizes the actuator solenoid valve to permit hydraulic flow and releases the mechanical lock on the stabilizer actuator, allowing series type automatic stabilizer axis control to provide pitch damping. Pitch attitude synchronization operates to automatically synchronize the stabilizer axis to the pitch of the aircraft during the stability augmentation mode and prior to the attitude hold mode.

PITCH DAMPER.—The pitch damper function provides a stabilizer deflection proportionate to and opposing aircraft pitch rate. The primary function of the pitch damper is to damper pitch-axis oscillation. The stability sensor for the pitch damper is the pitch rate gyro. The sensor output is shaped in the pitch rate gyro wipe-out channel before being inserted into the stabilizer AFCS servosystem (input summing junction (13)). The air data computer parameter control is identical in operation as previously discussed.

The wipe-out channel is a high pass filter that eliminates pitch damper opposition to sustained pitch rates. The wipe-out is accomplished by converting the sensor a.c. to d.c. in the demodulator section of demodulator-modulator Z100-2 and applying it to a 2-second RC lead network. The signal is reconverted to 400 Hz in the modulator portion of Z100-2 for parallel summation with other inputs to the actuator drive amplifier (summing junction (13)).

PITCH ATTITUDE SYNCHRONIZATION.—The pitch attitude reference for the AFCS is obtained from the back-to-back coupling of the inertial navigation system pitch attitude transmitter to the AFCS computer amplifier (pitch computer) control transformer. The pitch computer, consisting of an electromechanical dual ratio servo assembly which drives the pitch control transformer and position sector switches through a dual ratio gear train, provides continuous pitch attitude synchronization prior to and during the stability augmentation mode. The control transformer senses changes in the aircraft pitch attitude and develops a proportionate error signal.

This error signal is fed to the input of the pitch computer motor amplifier (summing junction (12), fig. 10-21) via unenergized relay K4006. The motor amplifier output drives the 2-phase instrument servomotor through the high speed gear configuration, maintaining the control transformer output at null. Integral with the motor is a tachometer that generates a voltage proportionate to motor speed. The tachometer output voltage is summed with the control transformer input to damp the servo loop. The pitch computer is alined relative to the INS and position sector switch orientation, so that its shaft position directly corresponds to aircraft pitch attitude from level flight. The functions of

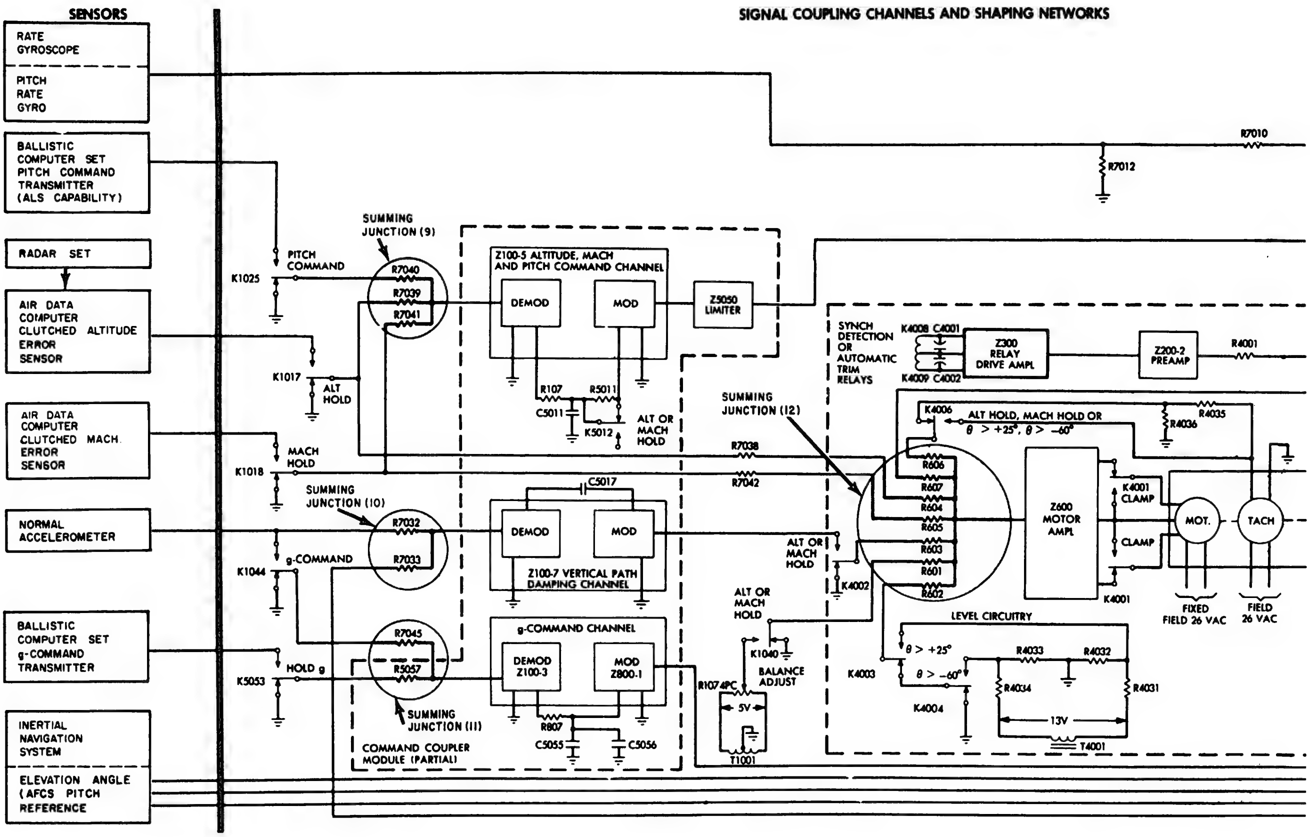

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Figure 10-21.—Stabilizer axis signal flow diagram.

the pitch computer sector switches and the low speed gear configuration are not required in the stability augmentation mode.

In stability augmentation mode, the pitch synchronization function is continuously and automatically monitored within the pitch computer. The control transformer output is coupled to a phase-sensitive relay amplifier via unenergized relay K1009. The relay amplifier energizes either relay K4008 or K4009 (depending on signal input phase) if the pitch computer fails to synchronize to within 2° of the aircraft's pitch attitude as sensed by the control transformer. When either relay is energized, the attitude hold mode cannot be energized. If synchronization is satisfactory and the attitude hold mode is engaged, relay K1009 is energized and the phase-sensitive relay amplifier is then switched to function as the automatic pitch trim control circuitry.

Attitude Hold Mode

Selection of the attitude hold mode allows automatic stabilizer control to provide pitch damping and pitch attitude hold. The attitude hold mode is identical to the pitch damper function previously described for the stability augmentation mode. Pitch attitude synchronization is stopped and the pitch computer control transformer error signals are applied to the AFCS servosystem. The aircraft pitch attitude is maintained by commanding stabilizer position proportional to pitch attitude displacement and rate errors. Automatic pitch trim functions in this mode and in all subsequent controller-engaged, series-actuator operating modes.

PITCH ATTITUDE HOLD.—The pitch attitude hold configuration is engaged when the attitude hold mode is selected. Aircraft pitch attitude displacement and rate deviations are sensed

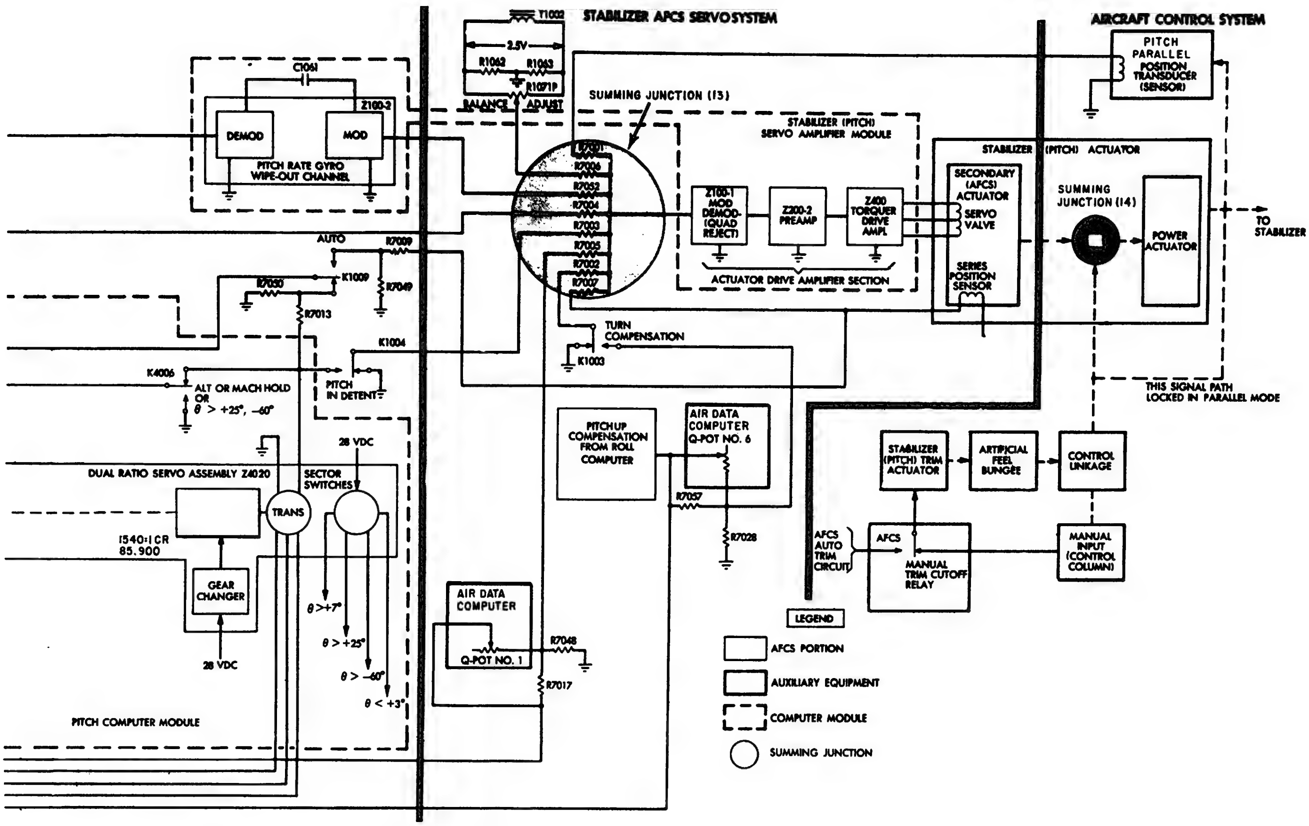

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Figure 10-21.—Stabilizer axis signal flow diagram—Continued.

and used proportionally to position the stabilizer to maintain the reference (engaged) aircraft attitude. Engaging the AUTO STAB-AUG switch on the controller disables attitude synchronization by clamping the pitch computer. Clamping is accomplished by short-circuiting the servomotor control field (relay K4001 energized). The clamped computer position establishes the reference attitude. Deviations from this attitude are sensed by the locked pitch computer control transformer. The INS pitch attitude transmitter detects the aircraft attitude changes which are then transformed to proportional a-c signals by the control transformer.

These pitch attitude deviation signals are fed to the input of the stabilizer AFCS servo system (summing junction (13)) through energized relay K1004 and command stabilizer deflection in a sense to maintain the reference attitude. (See fig. 10-21.) The use of relatively high attitude gains, required to maintain tight attitude control, dictate the need for aircraft attitude rate information for mode stabilization. Therefore, a signal proportionate to pitch rate is derived from the pitch rate gyro and summed with the control transformer attitude signals (summing junction (13)) to provide the phase lead (and, therefore, damping) required for stable system operation. The pitch rate gyro signal is passed through the pitch rate gyro wipe-out channel ahead of the summing point to eliminate opposition to sustained pitch rate commands. The wipe-out circuitry (high pass filter) is identical to that used in the rudder and flaperon axes.

The upper limits of pitch attitude hold are +25° pitchup and -60° pitchdown from level flight. If the aircraft pitch attitude is greater than either limit when the attitude hold mode is engaged, it will automatically pitch back to either +25° or -60°, depending on the respective limit

exceeded. Attitude synchronizatoin is continuous for all attitudes, thereby alining the pitch computer shaft with the actual aircraft attitude. When the AUTO STAB-AUG switch is engaged, the attitude sector switches (connected to the pitch computer shaft) energize relay K4003 if the pitch attitude is greater than +25° up, or relay K4004 if the pitch attitude is greater than -60° down. Relay K4006 is energized, removing the control transformer input to the pitch computer, thereby stopping synchronization and switching to full tachometer feedback. Relay K1004 is energized, inserting the control transformer output into the AFCS servosystem (summing junction (13)); and the level circuitry voltage is inserted into the pitch computer (summing junction (12)). The phase of the level voltage depends on which relay (K4003 or K4004) is energized.

The level voltage establishes the pitch computer motor rotation rate which commands an aircraft pitch rate towards level via the control transformer input to the AFCS servosystem and the aircraft control system. The level voltages are adjusted to provide a maximum normal incremental acceleration of approximately +2.5 g when leveling to -60° and -0.8 g when leveling to +25° (in the high speed flight condition). The pitch computer is clamped and the level voltage removed when the shaft position of the sector switches indicates +25° or -60°. The aircraft will pitch until its attitude is in agreement with the pitch computer shaft position and the control transformer output is nulled, recentering the AFCS servosystem. The pitch attitude at either +25° or -60° is maintained in the same manner as described for pitch attitude hold.

AUTOMATIC PITCH TRIM.—Pitch trim is provided automatically when the attitude hold mode is engaged. Automatic trim is operative for all series operating modes of the stabilizer actuator with the exception of stability augmentation. The automatic pitch trim function relieves the AFCS from holding a pitch error and from holding AFCS actuator displacement to provide the sustained stabilizer deflections required to compensate for trim shifts due to changing flight configuration. This relief is accomplished by repositioning the control column and linkage to hold the required surface through the action of the stabilizer trim actuator on the stabilizer artificial feel bungee. This automatic pitch trim function assures that the stabilizer control system is trimmed. This removes the possibility of a disengage transient due to mistrim when the attitude hold mode is disengaged.

When the attitude hold mode is engaged, manual trim cutoff relay and relay K1009 are energized. The manual trim cutoff relay switches the input (excitation) to the stabilizer trim actuator from the stick-manual trim button to the AFCS automatic trim circuitry. (See fig. 10-21.) Relay K1009 switches the input to the pitch computer phase-sensitive relay amplifier circuitry from the pitch control transformer output to the AFCS actuator series position sensor output. When the aircraft trim condition alters, due to changes in the flight configuration, a pitch attitude change results. The pitch attitude change is sensed by the pitch computer control transformer, which commands stabilizer surface deflection in a sense to maintain the reference pitch attitude. A pitch attitude error (from the reference) proportional to the attitude change results in a steady-state surface deflection. This deflection is sensed by the series position sensor, which produces a proportional output voltage.

The position sensor output is fed to the input of the pitch computer relay amplifier via relay K1009. When the position voltage exceeds the relay amplifier pull-in voltage (equivalent to approximately 0.1° of stabilizer), and depending on the phase of this input (phase determines direction of surface deflection), either relay K4008 or relay K4009 is energized. Contacts of these relays in turn apply 120-volt a-c excitation to the low speed windings of the stabilizer trim actuator. The direction in which the electromechanical screwjack trim actuator moves depends on whether up trim or down trim is energized.

The stabilizer trim actuator output moves the aircraft's control column via the stabilizer artificial feel bungee. As noted in the stabilizer aircraft control system discussion, control column movement is summed with the AFCS output at the input to the power actuator. The control column input due to the trim actuator motion commands surface deflection in the same direction as that resulting from the actuator displacement. The increased surface deflection reduces the attitude error, which decreases the signal input to the AFCS servosystem. This decreased signal input returns the actuator towards its neutral position and decreases the series position sensor output. This action continues until the actuator approaches the neutral position. At this point, the position sensor

voltage reaches the relay amplifier dropout voltage, thereby stopping the trim actuator. The net result is that the surface position required for trimmed flight is obtained from control column input and the AFCS servosystem operates about its neutral (no input) position.

The stabilizer trim actuator has separate manual and AFCS input windings to provide a two-speed capability. The AFCS automatic trim input has a trim speed approximately one-twentieth of the manual rate. The slower rate associated with automatic trim is required to assure stable system operation.

Altitude Hold Mode

The AFCS provides longitudinal flightpath control to the barometric altitude existing at the time of altitude hold mode engagement. At altitudes below 5,000 feet, the barometric altitude error signal is modified in the air data computer by a radar altimeter climb-dive signal to correct for altitude hold deviations caused by ambient barometric pressure changes. The altitude hold function is accomplished by commanding pitch attitude proportional to altitude displacement, integral, and rate error inputs. The altitude hold mode is selected via the ALT switch on the controller.

Selection of the altitude hold mode energizes relays K1017, K1040, K1070, K4002, and K4006 (fig. 10-21), engages the air data computer altitude sensor clutch, and converts the pitch computer into an electromechanical integrator. Contacts of relay K1017 switch the engaged altitude sensor output into the input of the altitude, Mach, and pitch command channel (summing junction (9)), and into the input of the pitch computer (summing junction (12)). Contacts of relay K1040 switch the pitch computer balance adjust potentiometer (R1074PC) into the input of the pitch computer (summing junction (12)). Relay K4002 couples the vertical path damping channel output into the pitch computer (summing junction (12)). Relay K4006 removes the control transformer input to the pitch computer, enabling it to run open loop (integrate), and switches in the full tachometer signal. In addition to breaking the position feedback (removing the control transformer input), the pitch computer reduction gearing is increased (by applying 28 volts d.c. to the gear changer) from 1,540:1 to 85,900:1 to achieve the required slow integration rate.

An a-c signal proportional to altitude displacement from the barometric reference, derived from the clutched, spring-centered transducer in the air data computer, is used to establish the displacement and integral error control signals. The displacement control is accomplished by commanding pitch attitude proportional to the altitude sensor output. The sensor signal is fed through the altitude, Mach, and pitch-command channel to the input of the stabilizer AFCS servosystem. The altitude, Mach, and pitch-command channel filters and limits the input error signal.

In this channel, the a-c sensor signal is demodulated, filtered (2-second time constant RC lag circuit), and modulated to 400 Hz for signal summation at the input to the AFCS servosystem (summing junction (13)). Filtering this signal minimizes the angle-of-attack effects on the altitude displacement control signal. The output response from the AFCS servosystem commands stabilizer displacement, which results in an aircraft pitch rate. The aircraft pitch attitude changes until the attitude error signal input (from the pitch computer control transformer) to summing junction (13) cancels the altitude error input, thus returning the surface to neutral and stopping the pitch attitude change. Pitch attitude change, proportional to altitude error, maintains the barometric reference. The maximum pitch attitude command from the altitude displacement signal is limited to ±13.5° of pitch attitude because of the altitude, Mach, and pitch-command channel limiter.

If the altitude hold mode were engaged with the aircraft in other than level flight, and the altitude displacement error were the only control, a sustained altitude error (standoff from the reference) would result. Assuming the aircraft was in a climb at the time of engagement, the altitude hold function would try to maintain the climb attitude, and the altitude error signal would try to change the attitude sufficiently to return the aircraft to the barometric reference. An altitude error sufficient to change the aircraft pitch attitude to level (no further increase in altitude) would be required to cancel the pitch control transformer output resulting from the attitude change (climb to level). Ultimately, an altitude signal and attitude signal would be summed at summing junction (13) to produce a zero input to the servosystem.

Disengagement of the altitude hold mode de-energizes relays K1040, K1070, and K4002. Relay K1070, however, has a time delay circuit

which holds it energized for 2 seconds after interlock voltage is removed. One set of relay K1070 contacts applies the full pitch computer tachometer signal to be summed into the pitch computer (summing Junction (12)) for 2 seconds. During this 2-second period the pitch computer smoothly synchronizes to a null, thus removing the integrator output and providing altitude hold mode easy disengage. Relay K1070 also holds relay K1004 energized for this 2-second period to prevent the pitch computer control transformer output from being switched out of the AFCS servosystem until it is properly synchronized.

The use of relatively high altitude hold gains (required for tight altitude control) and the added lag contributed by the displacement signal filter dictate the need for aircraft altitude rate information for mode stabilization. An altitude rate signal is developed by integration of aircraft normal (vertical) acceleration, which is summed with the altitude displacement and integral signals to provide the phase lead (and, therefore, path damping) required for stable system operation. The center-of-gravity-mounted normal accelerometer provides the signal proportional to aircraft normal acceleration. This signal is fed to the pitch computer (summing junction (12)) via the vertical path damping channel. This channel is a high pass filter that wipes out steady-state input signals such as noise and nulls. It consists of a demodulator (Z100-7), an RC lead network (25-second time constant), and a 400-Hz modulator (Z100-7). In the control frequency spectrum, the output of this channel is proportional to altitude acceleration. This output signal, converted to an altitude rate signal by integration through the pitch computer, commands pitch attitude proportional to altitude rate deviations.

A signal proportional to the aircraft bank angle, derived from the cosine winding of the roll computer resolver, is summed with the normal accelerometer signal at the input to the vertical path damping channel (summing junction (10)). This signal is calibrated to provide approximate cancellation of the normal accelerometer output resulting from aircraft turn maneuvers. A turn command (aircraft bank) produces a change in aircraft load factor (normal acceleration) which is sensed by the normal accelerometer, thus causing an output corresponding to a nonexistent change from the reference altitude. Cancellation of this signal eliminates the erroneous altitude change from the reference that this signal would command. The wipe-out action of the vertical path damping channel eliminated the steady-state effects of mismatch between the resolver and accelerometer signals.

In conclusion, the AFCS barometric altitude control commands aircraft pitch attitude. The pitch attitude is proportional to integral plus displacement signals at the low frequency portion of the control spectrum and proportional to only displacement signals in the midfrequencies. It is proportional to displacement plus rate signals in the high frequency portion of the control spectrum.

The AFCS provides longitudinal flightpath control to the Mach number existing at the time of Mach hold mode engagement. The Mach hold function is accomplished by commanding pitch attitude proportional to Mach number displacement and integral, and to vertical path rate deviations. The Mach hold mode is selected via the Mach switch on the controller. The theory of signal operation of the Mach hold mode is the same as for altitude mode and is not repeated.

Control Stick Steering Mode

The AFCS is implemented for control stick steering; that is, pilot-applied stick force reverts the system back to the stability augmentation mode while the aircraft is maneuvered manually. With the attitude hold mode engaged, application of longitudinal stick force (1.1 lb) sufficient to actuate the force-sensitive switches in the pilot's stick removes the pitch attitude reference from the system (deenergizes relay K1004), and causes the pitch computer to revert to the synchronization phase. Continued force results in a manual input to the stabilizer aircraft control system (summing junction (14)), producing stabilizer deflection and an aircraft pitch rate.

While the stick force is applied, the AUTO STAB-AUG switch on the controller remains engaged and the AFCS stability augmentation mode functions, as described in the stabilizer axis discussions, providing pitch damper control. In the stabilizer axis, the manually commanded pitch attitude is continuously synchronized as described previously. If the altitude or Mach hold mode has been selected prior to the application of longitudinal stick force, the respective engage switch will disengage with stick force application, thus removing the particular control function. Upon release of the stick, the attitude

hold mode is automatically reengaged in the pitch attitude hold configuration. If the command mode (via the CMD switch) has been selected prior to the application of longitudinal stick force, it remains engaged and the command mode control function automatically regains control upon release of the stick (except for the ALS data link phase). A summary of AFCS operation is presented in table 10-3.

AFCS INTERLOCK

The interlock provisions of the AFCS establish the system configuration and function consistent with the selected operating mode. Each mode is interlocked to prevent selection of incompatible functions. Visual indication of the current operating mode is presented by controller switch identification.

The AFCS interlock system generally operates off the 28-volt d-c supply. The mode select switches on the controller are solenoid-held toggle and pushbutton switches, with the exception of the return to level switch which is the momentary-on, pushbutton type. The solenoid held type of switch is ideally suited to interlock systems in that the solenoid excitation may be applied directly through the respective switch or indirectly through relays and/or other switches. Therefore, the switching voltage and the solenoid voltage may be one and the same, eliminating the possibility of selecting an incompatible mode. Most of the signal and interlock switching is accomplished by operation of standard double-pole, double-throw relays. All the switching relays are in the computer, with the majority of them located in the electrical equipment rack, and the remainder within the various modules of the computer. Detailed theory of operation of the interlock system and circuitry is found in NavAir 01-85ADA-2-5.1.

Table 10-3.—Summary of AFCS operation.

Mode of operation	Switching and signal data	Signal input axis
STABILITY AUGMENTATION	Controller: ON-OFF switch—ON AUTO STAB-AUG switch—STAB-AUG	—
Damper	Rate gyroscope: Roll, yaw, and pitch rate signals	Rudder, stabilizer, flaperon
Attitude synchronization	Inertial navigation system: Roll angle and elevation angle signals	Rudder, stabilizer, flaperon
Heading synchronization	Inertial navigation system: True heading signal	Flaperon
ATTITUDE HOLD	Controller: ON-OFF switch—ON AUTO STAB-AUG switch—AUTO	—
Roll attitude hold	Aircraft: Roll attitude more than 5° but less than 60°	Flaperon
	Inertial navigation system: Roll angle signal	—
Automatic pitch trim	Stabilizer actuator: Series sensor position signal	Stabilizer
Pitch attitude hold	Aircraft: Pitch attitude between +25° pitchup, and -60° pitch-down	Stabilizer
	Rate gyroscope: Pitch rate signal	—
	Inertial navigation system: Elevation angle signal	—
Heading hold	Aircraft: Roll attitude between 0° and 5°	Flaperon
	Inertial navigation system: True heading signal	—
ALTITUDE HOLD	Controller: ON-OFF switch—ON AUTO STAB-AUG switch—AUTO ALT button—depressed	Stabilizer
	Normal accelerometer: Normal acceleration signal	—
	Air data computer: Altitude error signal	—

Table 10-3.—Summary of AFCS operation—Continued.

Mode of operation	Switching and signal data	Signal input axis
MACH HOLD	Controller: ON-OFF switch—ON AUTO STAB-AUG switch—AUTO MACH button—depressed	Stabilizer
	Normal Accelerometer: Normal acceleration signal	—
	Air data computer: Mach error signal	—
RETURN TO LEVEL	Controller: ON-OFF switch—ON AUTO STAB-AUG switch—AUTO RETURN TO LEVEL switch NOTE: At completion of the return to level maneuver, the flaperon and stabilizer axes revert to the heading hold and pitch attitude hold configurations, respectively.	Flaperon and stabilizer
COMMAND	Controller: ON-OFF switch—ON AUTO STAB-AUG switch—AUTO CMD switch—ON	
Roll command	Ballistic computer set: Discrete (28 volts d. c.) roll command available signal Roll angle command signal	Flaperon
	Inertial navigation system: Discrete (28 volts d. c.) 90° flipping signal (inverted flight)	—
RETURN TO LEVEL	Ballistic computer set: Discrete (28 volts d. c.) return to level signal	Flaperon and stabilizer
G-command	Ballistic computer set: G-command signal	Stabilizer
GROUND CONTROLLED BOMBING (TPQ-10)	Controller: ON-OFF switch—ON AUTO STAB-AUG switch—AUTO	Flaperon
	Aircraft: Heading hold configuration	—
	GCBS control panel: TPQ-10 ENGAGE switch—ON	—

CHAPTER 11

INERTIAL NAVIGATION

The introduction of inertial navigation systems into naval aircraft creates a whole new set of problems in operation, maintenance, and deck handling. This chapter introduces some of the fundamental concepts of inertial navigation and discusses some of the types of inertial navigation systems presently in use.

FUNDAMENTALS OF INERTIAL NAVIGATION

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Navigation may be defined as the process by which one directs a vehicle from one point to another. Basically, navigation can be divided into two categories: (1) position fixing and (2) dead reckoning. In the first category, position is determined by your position relative to positions of known objects such as stars and landmarks. The most common example of this is celestial navigation. Loran is another example of navigation by periodic position fixes. The second category, dead reckoning, is the process of estimating your position from the following known information:

1. Previously known position.
2. Course.
3. Speed.
4. Time traveled.

Examples of this category are the Doppler radar and the inertial navigators.

All navigation systems, except inertial, rely on some bit of information external to the vehicle to solve its navigational problem. In this respect the inertial navigator stands alone. It is completely self-contained within the vehicle. It is independent of its operating environment, such as wind, visibility, or aircraft attitude. It does not radiate RF energy; therefore, it is impervious to countermeasures. It does not depend on ground transmission or any other outside source to determine its instantaneous position. The inertial navigator simply makes use of the physical laws of motion that Newton described three centuries ago.

BASIC PRINCIPLES

Perhaps the most important part of Newtonian physics on which the concepts of inertial navigation systems are based is described by Newton's First Law of motion: "Every body continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed on it."

The full meaning of Newton's First Law is not easily visualized in the earth's reference frame, for Newton's laws apply in an inertial reference system. As inertial reference system may be defined as a nonrotating coordinate frame, either stationary or moving linearly at a uniform speed, in which there are no inherent forces, such as gravity.

A simple test of whether one is in a true inertial system can be made by having the observer release an object and observe its motion. If the object is released without imparting any acceleration to it, the object will remain in its position relative to the observer; if the object is thrown, it will continue on an undeviating path at a constant speed. Such a system can only exist in empty space, far from any mass, for all masses contain gravitational forces. A reference system attached to the earth can closely approximate an inertial system when the gravitational forces on a body is balanced out by a second force. For example, an object sliding on a flat frictionless plane on the surface of the earth would move in a NEARLY straight line with a NEARLY constant speed, as seen by an observer in the earth's coordinate system.

NOTE: The word NEARLY is emphasized because the object will deviate slightly from its straight-line motion because of the earth's rotation about its axis.

Newton's Second Law of motion shares importance with his First Law in the inertial navigator, for it is Newton's Second Law that the inertial navigator is constructed to apply.

Newton's Second Law of motion states: "Acceleration is proportional to the resultant force and is in the same direction as this force." Thus, the Second Law is written

$$F = ma$$

where

$$\begin{aligned} F &= \text{force} \\ m &= \text{mass} \\ a &= \text{acceleration} \end{aligned}$$

Now, the physical quantity in the foregoing equation in which the inertial navigator is interested is acceleration; because from acceleration, velocity and displacement can be derived. For example, consider this fact: Before an object can change its state of rest or state of motion, it must first experience an acceleration; and since acceleration is a change in velocity and velocity is a change in position, then acceleration is a change in the change of position. However, before any change can have meaning, it must include the unit time. Therefore, a change per unit of time is defined as a rate-of-change. Thus, a rate-of-change of displacement is velocity; a rate-of-change of velocity is acceleration; and a rate-of-change of a rate-of-change in displacement in acceleration. Written mathematically gives

$$\frac{ds}{dt} = v$$

$$\frac{d^2s}{dt^2} = \frac{dv}{dt} = a$$

where ds/dt is defined as the rate-of-change of displacement "s" with respect to time and d^2s/dt^2 is the rate-of-change of the rate-of-change of displacement "s" with respect to time.

The equations given above are from calculus and are called derivatives. The act or process of taking derivatives is called differentiation. In calculus, the act or process that reverses the operation of differentiation is called integration. Differentation is the process of investigating or comparing how one physical property varies with respect to another; integration, the reverse of differentiation, is the process of summing all rate-of-changes that occur within the limits being investigated.

The inertial navigator is not a differentiating device; it is an integrating device. However, before integration can be done, a rate-of-change must first be supplied. Thus, the inertial navigator, when stripped to its barest essentials, is a detector and an integrator. It first detects rate-of-changes of motion, and then it integrates these rate-of-changes of motion which gives velocities and displacements.

Fundamentals of Integration

Since the inertial navigator is partly an integrating device, a simplified explanation and an applied example are given. First, consider the integrals of acceleration and velocity given as

$$\begin{aligned} \int a \, dt &= v \\ \int v \, dt &= s \\ \iint a \, dt \, dt &= s \end{aligned}$$

where

$$\begin{aligned} s &= \text{displacement} \\ v &= \text{velocity} \\ a &= \text{acceleration} \\ \int &= \text{integration symbol} \\ dt &= \text{time differential} \end{aligned}$$

The integral equations above show that when acceleration is integrated with respect to time, the result is velocity; when velocity is integrated with respect to time, the result is displacement. Also, when acceleration is integrated twice (double integral) with respect to time, the result is displacement.

Recall from elementary physics that acceleration whose units are ft/sec^2, multiplied by time in seconds is velocity in ft/sec. Also, that velocity (ft/sec) multiplied by time (sec) is displacement (ft). The integration of acceleration, for example, is the mathematical process of summing all minute acceleration-time increments over a given time period, the result of which is velocity over the same time period. The same process done on velocity gives displacement or distance traveled over the same time period.

An example of how a simple single-axis inertial navigator works is illustrated as follows: A man has an acceleration detecting device, an integrating device, and a displacement readout device strapped to his back. The acceleration detecting device is only capable of detection along one line and is oriented in the backpack so that it detects accelerations when the man is

moving forward or backward, but not sideways or up and down (bobbing). Figure 11-1 is a block diagram of such a device.

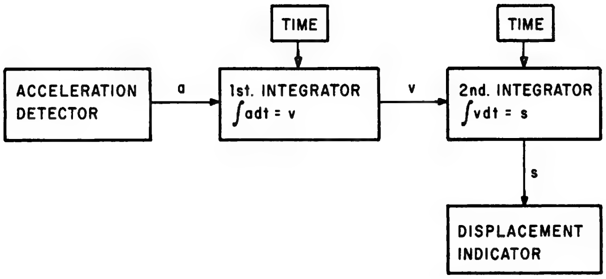

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Figure 11-1.—Simple single-axis inertial navigator block diagram.

The man starts at the reference point A, noting the reading on the displacement readout device at that point, and walks to point B, then stops. The readout device now indicates the new position, which is the distance traveled directly from point A to point B added to the reference value noted at point A. The man returns to point A by walking backwards so as not to disorient his simple inertial device. At point A his readout device indicates the value that was chosen as a reference, which is the displacement at point B minus the distance traveled directly from point B to point A.

Figure 11-2 (A) is a graph of the detected acceleration; (B) is the velocity curve obtained by integrating the acceleration curve shown in (A); and (C) is the displacement curve obtained by integrating the velocity curve shown in (B). All three curves are plotted as a function of time.

Before discussing the curves shown in figure 11-2, the central purpose of the inertial navigator is to keep track of position relative to some coordinate system. Also, the time intervals in figure 11-2 are nonlinear; they are marked at points of interest for convenience and clarity.

The acceleration curve (fig. 11-2 (A)) begins at time t_0 as the man begins his walk from point A in curve (C). The acceleration at time t_0 has a value of a_1 and it remains at that value until time t_1, where the man ceases to accelerate; therefore, acceleration goes to zero. At this point, terminal velocity is reached and is constant. The man continues walking at a constant velocity until time t_2 where he begins to stop. The acceleration detector detects an acceleration equal to value to a_1, but its direction is opposite. This acceleration is constant from time t_2 to time t_3, going to zero at time t_3. The man is now stationary and standing at his destination—point B.

Now, look at the velocity curve for the time interval t_0 to t_3, which is what is obtained when acceleration is integrated over the same interval—it is the output of the first integrator from t_0 to t_3. During the interval t_0 to t_1, velocity is changing in an increasing or positive direction. This means that an acceleration is taking place and is positive. Velocity is constant during time interval t_1 to t_2, which means that acceleration is zero. At time t2, velocity begins to decrease, which means that an acceleration is again taking place. In this case the acceleration is negative. At time t_3, both acceleration and velocity are zero.

Since the inertial navigator's purpose is to keep track of position and not total distance traveled, it integrates all values of acceleration (positive and negative) detected over the time interval. Therefore, it is the net value of acceleration in which the inertial navigator is interested. For instance, in the time interval t_0 to t_3, all accelerations that occur over the time interval are summed, which gives a net value at time t_3. In this case, integration of acceleration (curve (A)) is the process of summing the area bounded by the acceleration curve and the time axis, where the area above the time axis is positive and the area below the time axis is negative. Since the area above the time axis is equal to the area below the time axis, the net value of acceleration for the interval t_0 to t_3 is zero. The integral of acceleration for the interval t_0 to t_3 is therefore zero, which means that the velocity at time t_3 is equal to the velocity at time t_0, which in this case is zero.

Now, integrating velocity from time t_0 to t_3 (which is the job of the second integrator) gives B units of displacement on the displacement axis at time t_3. The displacement readout device changes continuously as long as the second integrator produces an output. The second integrator ceases to produce an output when the first integrator (velocity) ceases to produce an output. The velocity integrator continues to produce an output until it receives an acceleration which balances out the initial acceleration, thus producing a net acceleration of zero. The

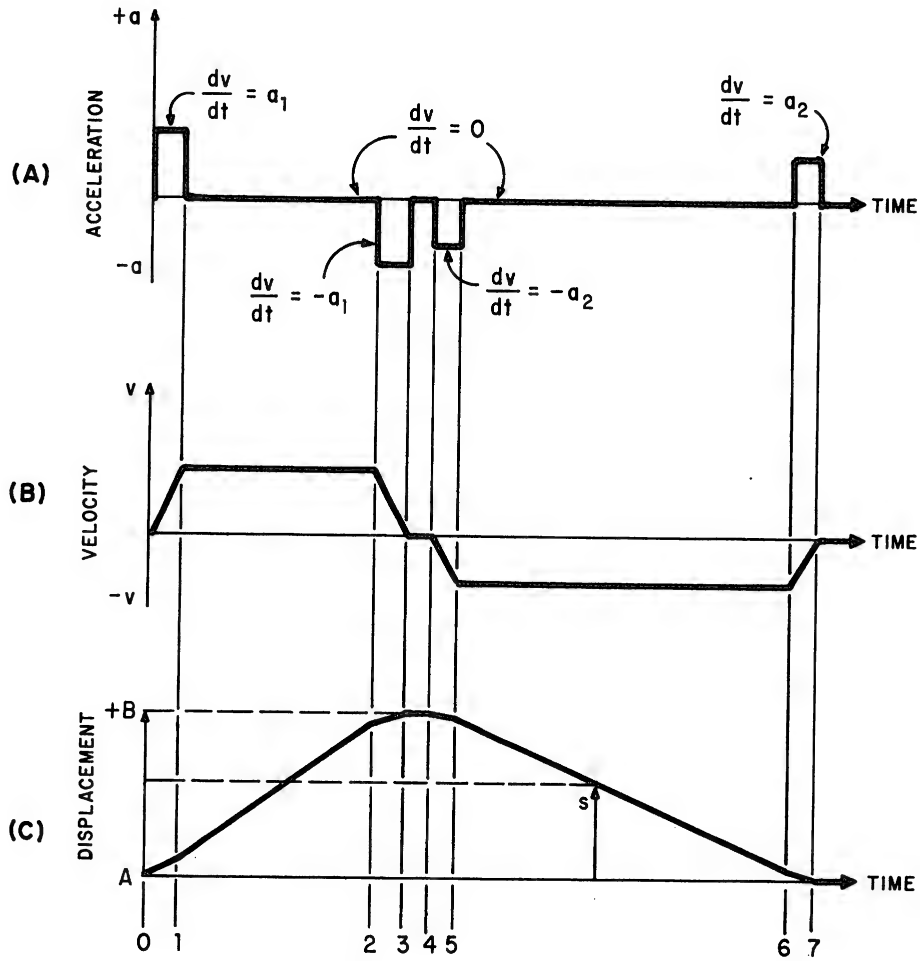

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Figure 11-2.—Integration of acceleration and velocity. (A) Acceleration; (B) velocity; (C) displacement.

readout device stops at the point where the net acceleration is zero. Until this condition is reached, the readout device indicates continuous change in displacement.

The return trip is described as follows: The man pauses at point B for time interval t_3 to t_4, then begins walking backwards to point A at time t_4. The acceleration detector detects an acceleration $-a_2$, which is negative and slightly less than the previous acceleration, $-a_1$. At time t_5 the terminal velocity is reached and acceleration goes to zero at this point. Note also that velocity is now negative since the direction of travel is reversed. Since the magnitude of acceleration, $-a_2$, is less than that of a_1, the terminal velocity on the return trip is less and, therefore, the time required to return to point A is greater. This is shown by time interval t_4 to t_7 greater than time interval t_0 to t_3. When the man is nearly at point A, he begins to stop, which is at time t_6, producing an acceleration a_2 as detected by the acceleration detector. He comes to a full stop at time t_7 where his detector detects zero acceleration. Since the net acceleration over the interval is again zero, the output of the first integrator (velocity) is zero; the output of the second integrator (displacement) is zero; and the displacement readout device is indicating the reference value that was originally noted at point A.

The simple inertial navigator just described will detect and compute all changes in displacement PROVIDED the acceleration detector (accelerometer) retains its straight-line orientation and all motion is along a straight line passing through the reference or initial point.

With this simple inertial navigating device, the man is restricted to navigation along a straight line, and on the return trip he must walk backwards (unless he unstraps the device from his back and sets it down, and then turns around and straps it to his chest, then proceeds walking forward).

Two-Axis Inertial Navigation System

Suppose, for example, that the earth is flat. If so, position can be determined by the use of a system of coordinate axes. This system of coordinates is defined as two sets of parallel lines (x and y) in which one set of lines is perpendicular to the other set of lines, thus forming a grid network over the earth's surface.

Now, if two single-axis inertial navigating devices are used, position on the plane (flat surface) can be determined by simply maintaining proper orientation of each accelerometer's sensitive axis relative to the coordinate system. That is, one accelerometer is mounted on a platform so that its sensitive axis lies along the x-axis, and the other accelerometer is mounted on the same platform so that its sensitive axis lies along the y-axis, thus maintaining their axes mutually perpendicular. The accelerometers will then sense any rate of change of velocity along the coordinate axes. Figure 11-3 is a block diagram of a simplified two-axis inertial navigation system.

Figure 11-4 is an illustration of the inertial platform mounted on a vehicle moving over a plane coordinate system. Note that the platform and accelerometers remain oriented with the coordinate axes regardless of the heading of the vehicle. Displacement of the vehicle over the grid system is represented by the vehicle's ground track, which can be located by the x, y coordinates at any given time. The x-displacement is plotted horizontally, and the y-displacement is plotted vertically. Time is referenced to the x-axis.

Figure 11-5 is an illustration of a typical set of acceleration and velocity curves obtained from the inertial navigation system shown in figure 11-4.

Referring to figures 11-4 and 11-5, the operation of the plane inertial navigation system is explained as follows: The vehicle is alined (initialized) on the coordinate system with a displacement of 3 on the x and y axes; that is, both x and y displacement indicators are set to read 3. At time t_3, the vehicle experiences an acceleration, A, in a direction of 45° from the x-axis. The accelerometers detect only that portion of the acceleration that lies along its sensitive axis; that is, the x-accelerometer detects the component of acceleration along the x-axis, which is A cos α, and the y-accelerometer detects the component of A along the y-axis, which is A sin α. The vehicle continues in a direction of 45° until time t_{15}, at which time it begins a turn to the right. Since the sine and cosine are equal to each other at the angle 45°

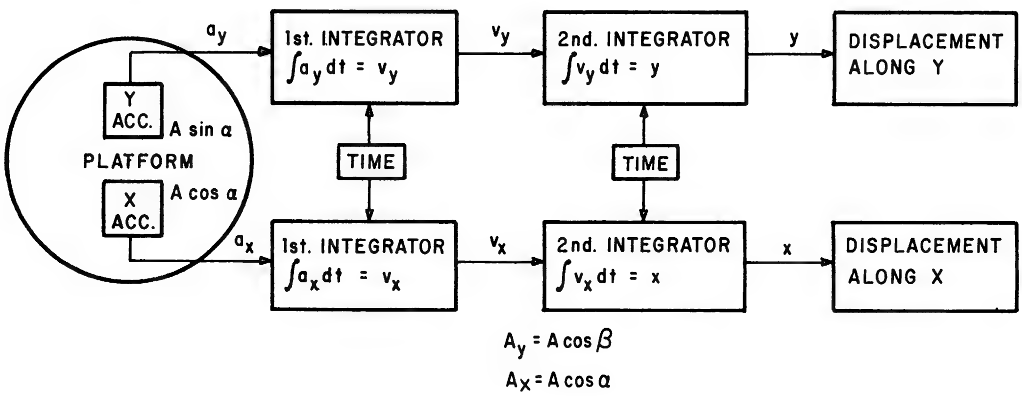

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Figure 11-3.—Two-axis inertial navigation system, block diagram.

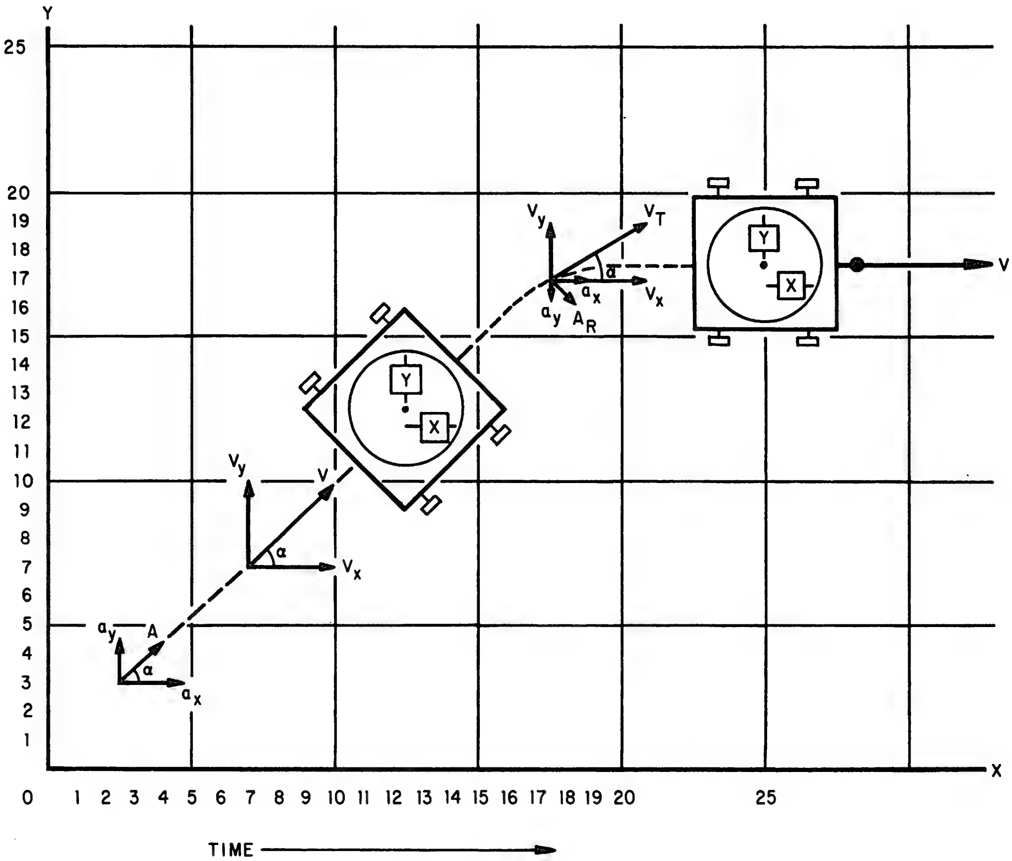

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Figure 11-4.—Two-axis inertial platform in a plane coordinate system.

(which means that the acceleration and velocity along the x-axis is equal to the acceleration and velocity along the y-axis), the displacements along x and y are equal at time t_{15}, which is x = 15 and y = 15.

At time t_{15}, the vehicle begins a turn to the right, completing the turn at time t_{20}. The new direction is parallel to the x-coordinate and normal (perpendicular) to the y-coordinate. Referring to figure 11-5 for the time interval t_{15} to t_{20} shows that the x-accelerometer detects a positive acceleration while the y-accelerometer detects a negative acceleration. If the speed of the vehicle is maintained constant throughout the turn, the detected acceleration results from a velocity change which is due to a change in direction rather than a change in speed. This acceleration is called RADIAL (centripetal) acceleration, A_R, and is directed toward the center of the turn and perpendicular to tangential velocity, V_T, as shown at coordinates (17.5, 17) in figure 11-4. Had the speed not been constant during the turn, a tangential acceleration, A_T, would have occurred, which would be parallel to the tangential velocity vector and normal (orthogonal) to the radial acceleration vector. Its direction would depend upon whether the speed was increasing or decreasing, positive or negative. Had the acceleration, which resulted from the vehicle's turning, been due to both a change in speed and direction, the accelerometers would have detected the x and y components of the resultant of the two accelerations.

The important point to note about detecting acceleration of an accelerating body is that the accelerometers detect only the component of the resultant acceleration along their sensitive axis. The accelerometers have no way of telling whether the detected velocity change is due to a speed change or a direction change or both; nor does it matter what forces cause the

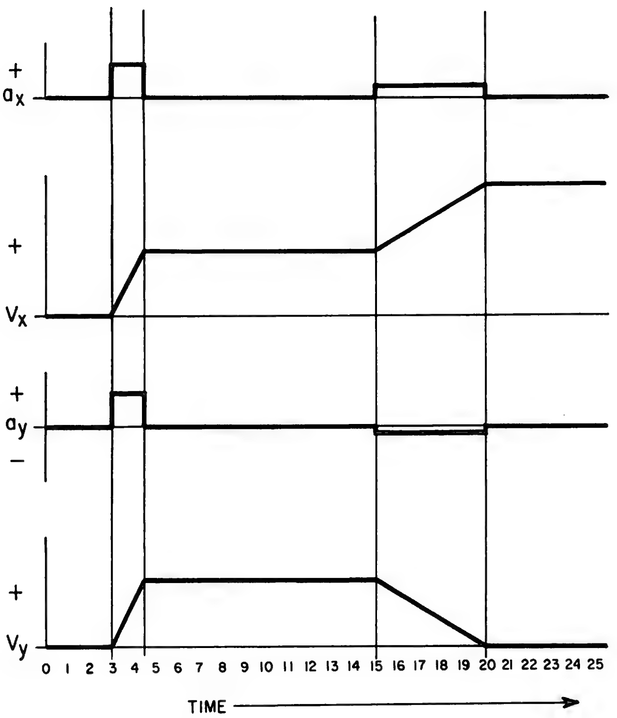

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Figure 11-5.—Acceleration and velocity curves.

velocity changes. The end result is the same provided the accelerometers maintain correspondence with the coordinate axes.

Referring to the acceleration and velocity curves in figure 11-5, the integration of the x-component of acceleration for the interval t_3 to t_{20} shows an increase in the x-component of velocity and, therefore, a corresponding increase in displacement along the x-axis. Integration of the y-component of acceleration over the same interval shows that the velocity goes to zero at time t_{20}; therefore, the displacement along the y-axis ceases to change. Hence at time t_{15}, the displacement is (15,15); at time t_{20}, the displacement is (20,15); at time t_{25}, the displacement is (25,15), etc.

The inertial navigation system just described will navigate very well on a flat surface; however, to navigate on the earth requires a more highly complex inertial system. The earth of course is not flat, and it is not exactly round either. Its radius at the poles is less than its radius at the equator. It also spins about its polar axis and orbits around the sun. All of these things must be taken into account and corrected for (except the earth's motion in orbit around the sun) before navigation on the earth by inertial means can be realized. The earth's motion about the sun does not affect an earth inertial navigation system because this motion is translational which is shared equally by all points on the earth.

BASIC SYSTEM COMPONENTS

The inertial navigation system measures aircraft accelerations to continuously compute aircraft velocity and change in present position. These measurements are made by precision inertial devices mounted on a 3-axis stable element which is, in turn, part of a four gimbal structure. The four gimbal structure allows the stable element to move 360° of freedom about the three axes.

Two gyros provide gimbal stabilization signals to maintain the stable element level with the earth's surface and alined to true north and to measure aircraft pitch and roll attitude. The inertial characteristics of the gyroscopes employed in the system are used to define and maintain the reference axes for relatively long periods of time and with great accuracy. With a gyro stabilized platform as a reference, it is possible to accurately detect the desired components of motion in any direction using precision accelerometers, integrators, and analog computers.

Accelerometers

The primary data source for this method of navigation is the accelerometer. Three accelerometers, mounted on the stable element between the gyros, provide output signals proportional to total accelerations experienced along the three axes of the stable element. The accelerations are supplied to analog computers to produce aircraft velocities and change in present position.

An accelerometer consists of a pendulous mass which is free to rotate about a pivot axis in the instrument. Figure 11-6 shows one form of this device. It has an electrical pickoff which converts the rotation of the test mass about the pivot axis to an output signal. An acceleration of the device to the right causes the pendulum to swing to the left, thereby providing an electrical pickoff signal which causes a torquer to restrain the pendulum. The pickoff signal is

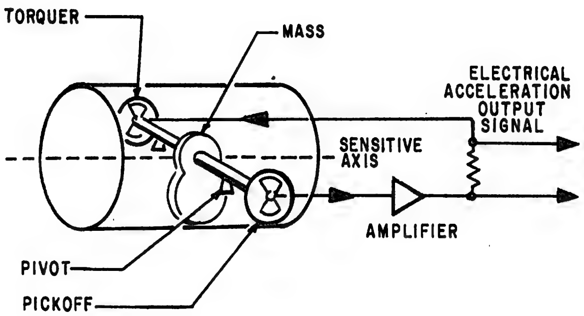

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Figure 11-6.—Typical torque-balanced accelerometer.

supplied to a high gain amplifier, and the output of the amplifier is connected to the torquer on the accelerometer. The operation of this feedback loop is such that when an acceleration is present, a voltage is sent to the torquer which holds the pickoff signal at a null under the influence of the measured acceleration. This voltage is proportional to the measured acceleration and provides the electrical output acceleration signal, e_o, which is supplied to the computer.

The accelerometer cannot distinguish between the acceleration of the vehicle and gravitational acceleration. Therefore, if the accelerometer is tilted off level, as shown in figure 11-7 (C), its output will include a component of gravitational acceleration as well as the vehicle acceleration. To obtain the correct vehicle acceleration in the horizontal plane, it is necessary to hold the sensitive axis of the accelerometer normal to the gravitational field, as shown in figure 11-7 (B).

If the accelerometer is mounted on a platform (stable element) in such a way that it is always held level, the accelerometer measures true aircraft acceleration in a horizontal direction, along the sensitive axis of the accelerometer. By mounting another level accelerometer perpendicular to the first one, the total true acceleration in a horizontal plane is determined at all times.

Integrators

To convert the measured acceleration to aircraft position information, it is necessary to process the acceleration signals to produce

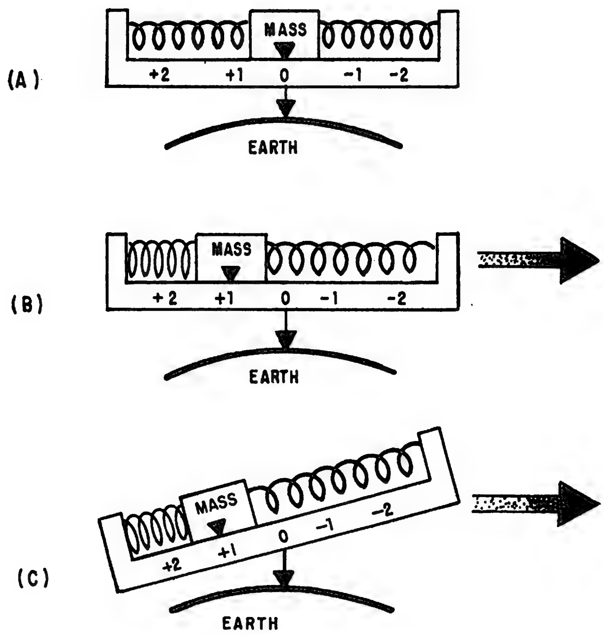

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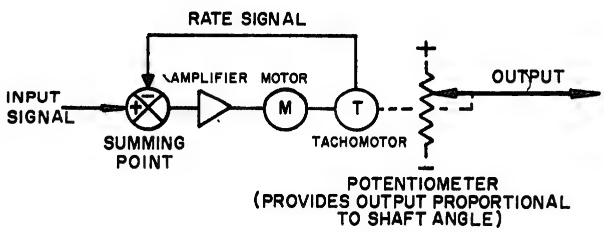
Figure 11-7.—Principle of accelerometer. (A) Accelerometer at null; (b) true acceleration; (C) spurious acceleration due to gravity.

velocity information, and then to process the velocity information to obtain distance traveled. A typical integrator used in inertial navigation systems is shown in figure 11-8. It is an electromechanical device which receives an electrical input (acceleration or velocity) and produces a shaft speed proprotional to the input. The shaft angle is the output of the integrator,



AE.632

Figure 11-8.—Typical inertial integrating device.

and it is the mathematical integral of the input. If the input is acceleration, the output is velocity; if the input is velocity, the output is distance.

If one of the horizontal accelerometers points north, the other one will always point east. By connecting the accelerometer outputs to integrators as shown in figure 11-9, distance traveled in the north-south and east-west directions can be determined. The importance of maintaining the proper accelerometer pointed north and of maintaining both accelerometers horizontal to the earth's surface is apparent. If the accelerometers tilt off level, gravitational components would be measured and navigation errors would result. A third accelerometer is mounted on the stable element in the vertical plane to determine vertical acceleration. The gravity component is subtracted from the output of the accelerometer by the computer. The resulting signal represents actual aircraft vertical acceleration. Vertical acceleration is supplied to an electronic integrator in the attitude computer which computes vertical velocity.

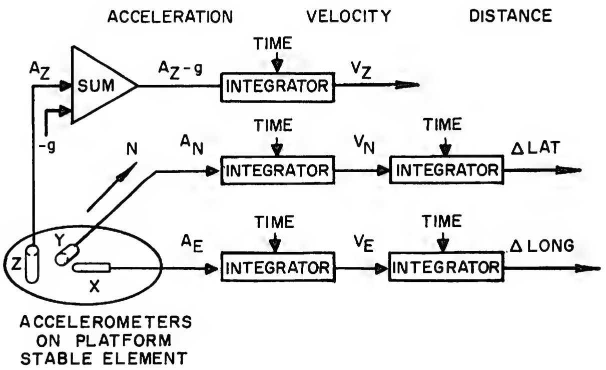


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Figure 11-9.—Basic inertial navigation system.

Platform Stable Element

Proper orientation of the accelerometers is maintained by mounting them on a stable element together with gyroscopes, which are the sensing elements for controlling the orientation of the stable element. The stable element (fig. 11-10) is mounted on gimbals which isolate it from angular motions of the aircraft.

GYROSCOPES.—The stable element contains two identical floated, two-degree-of-freedom gyroscopes, mounted one on top of the other in a dumbbell configuration (fig. 11-10), with their spin axes horizontal and at right angles to each other. The wheels in these gyroscopes, which spin at high speed, resist any effort to change the orientation of their spin axes.

Figure 11-11 shows a two-degree-of-freedom gyro and a single-axis stable platform. The pickoffs on the gimbals within the gyro produce electrical signals if the gyro case is moved from its null position with respect to the gyro motor. With the gyros mounted on the stable element, any displacement of the stable element from the frame of reference will be sensed by the electrical pickoffs in the gyroscopes. The signals thus created are used to drive the platform gimbals to realine the stable element.

PLATFORM GIMBAL STRUCTURE.—Figure 11-10 illustrates the four-gimbal platform configuration actually used in inertial navigation systems. The stable element is mounted in the gimbal structure so that regardless of what maneuvers are made by the aircraft, it retains the original orientation, thus serving as a level mount for the accelerometers. An azimuth gimbal permits the aircraft to change heading without affecting the orientation of the stable element. A pitch gimbal removes the effect of aircraft pitch, and a roll gimbal eliminates the effects of roll. An extra roll gimbal is provided which prevents the occurrence of gimbal lock during certain aircraft maneuvers and makes the system truly all-attitude. Referring to figure 11-12, the inner roll gimbal is provided to prevent gimbal lock, which would cause the stable element to tumble. Gimbal lock occurs when two of the gimbal axes become alined parallel to each other, causing the stable element to lose one of its degrees of freedom. When the aircraft exceeds 90° in pitch, the outer roll gimbal is rotated through 180°. The gimbals are oriented so that aircraft attitude and heading may be sensed by measuring angles between the gimbals. Synchros transmit this information to the attitude indicator and other systems in the aircraft.

Platform Orientation.—Figure 11-13 (A) illustrates the apparent rotation of a stabilized platform located at the equator. As shown, the platform will remain fixed with respect to inertial space, but it will appear to rotate with respect to the surface of the earth as the earth spins about its polar axis. This is undesirable from the point of view of navigation, since the accelerometers will not remain horizontal to the earth's surface, thus producing gravitational

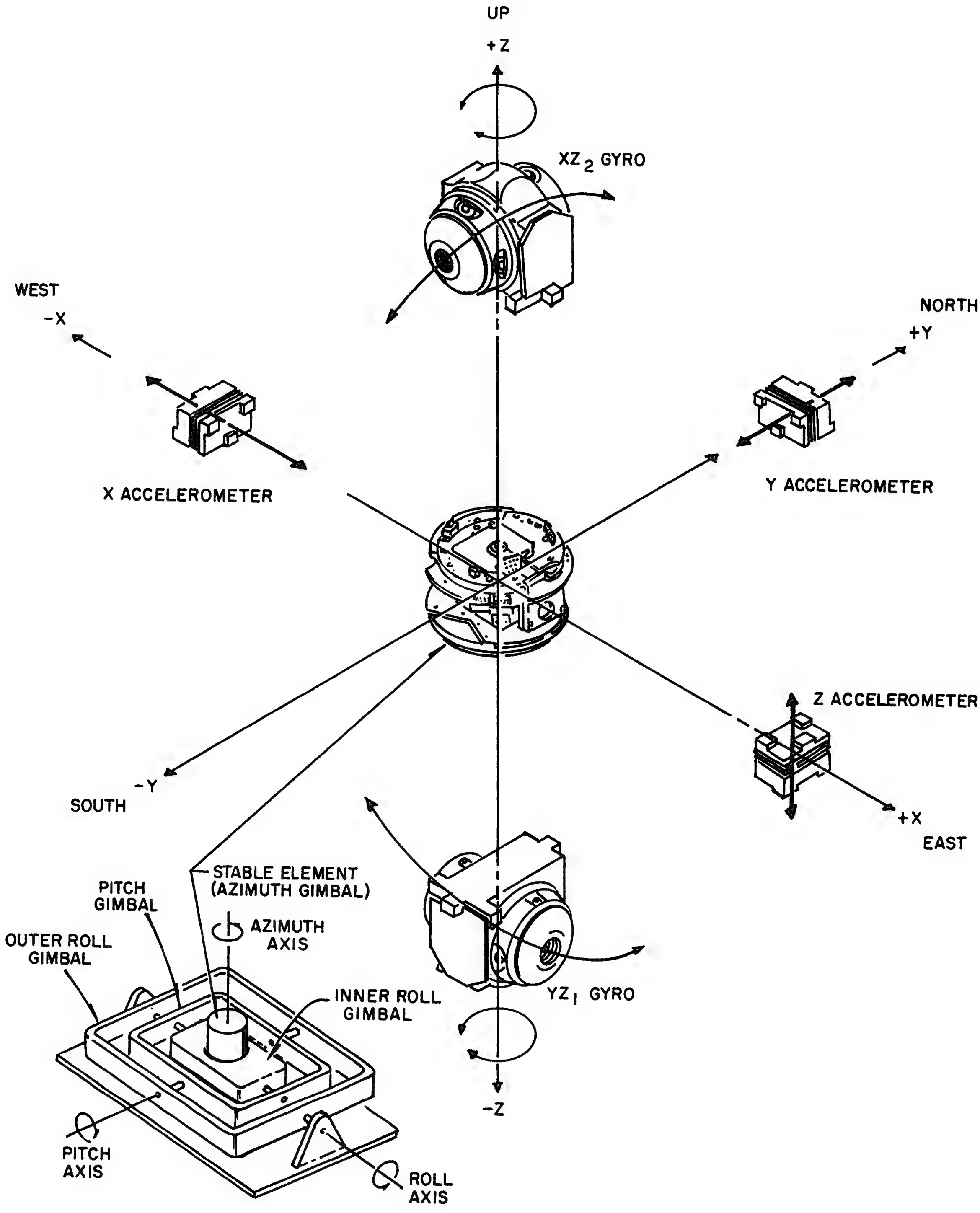

Figure 11-10.—Simplified platform stable element.

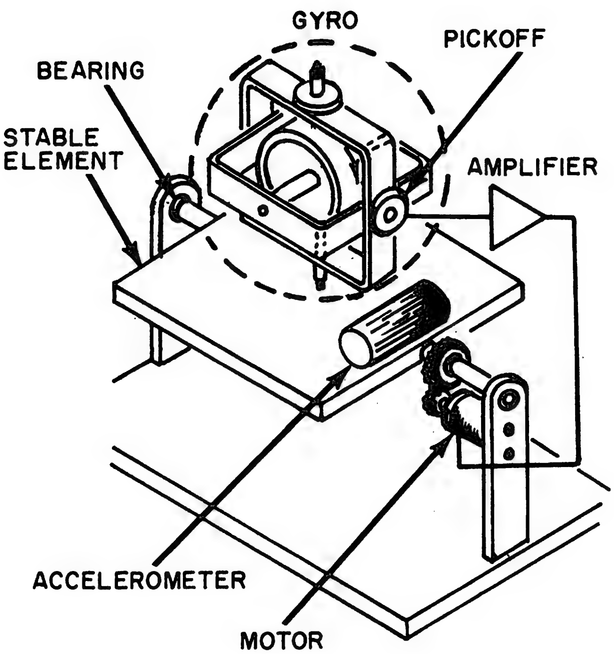

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Figure 11-11.—Single-axis, gyrostabilized platform.

components of acceleration in the outputs of the accelerometers.

Consider also what happens to a stable element which is alined properly at the beginning of a flight as the aircraft flies over the surface of the earth. If the aircraft flightpath is straight north from the equator to the north pole, as shown in figure 11-14 (A), the aircraft "sees" a continuing pitch maneuver. At the pole, instead of the platform being level with the surface of the earth, it would now be tilted 90° off level.

Gyro Torquing Computations.—To overcome the problems that arise from platform tilt, the gyroscopic property precession is used. By utilizing the gyroscopic principle of precession as the aircraft flies over the rotating earth, it is possible to apply a continuous torque to the appropriate axes, thereby reorienting the gyros to maintain the stable element horizontal to the earth's surface and pointed north. The operation of the platform with proper earth rate and aircraft rate torquing correction is shown in figures 11-13 (B) and 11-14 (B).

An electronic analog computer is used to develop the signals necessary to properly torque the gyros. The corrections for earth rate depend on the aircraft's position on the earth's surface. The corrections are derived from highly accurate potentiometers which produce trigonometric functions of aircraft position. The potentiometers are driven by the position integrator shafts. To maintain the stable element oriented to the north reference, torquing corrections are also applied to rotate the platform about the vertical axis to compensate for vehicle velocity.

Schuler Pendulum

A pendulum is any suspended mass, free to rotate about at least one axis, and its center of gravity is NOT on the axis of rotation. Therefore, any pivoted mass that is not perfectly balanced is, by definition, a pendulum. The inertial platform is a pendulous device and, therefore, behaves as all pendulums behave. They aline to the dynamic vertical when at rest, with the pivot axis and the center of gravity both in line with the gravity vector and with the center of gravity on the bottom. Also, they tend to break into their natural period of oscillation whenever the aircraft is accelerated.

Pendulous oscillation is periodic angular motion having the gravity vector as its midpoint. Periodic motion around the local vertical produces obvious errors from an inertial platform since misalinement relative to the horizontal plane introduces gravity components on accelerometer inputs. The system will interpret gravity accelerations as horizontal acceleration of the aircraft. The Schuler pendulum is a specially constructed pendulum that does not possess the unwanted oscillatory motions of non-Schuler pendulums. It is a special case of both the simple and the compound pendulums, which is illustrated in the following discussion on simple and compound pendulums.

SIMPLE PENDULUM.—The simple pendulum consists of a small body suspended by a weightless string. The motion of the simple pendulum is both periodic and oscillatory. The period of the simple pendulum is given by the mathematical formula:

$$T = 2\pi\sqrt{\frac{L}{g}}$$

where

T = time of one oscillation in seconds
L = length of the string
g = local gravity

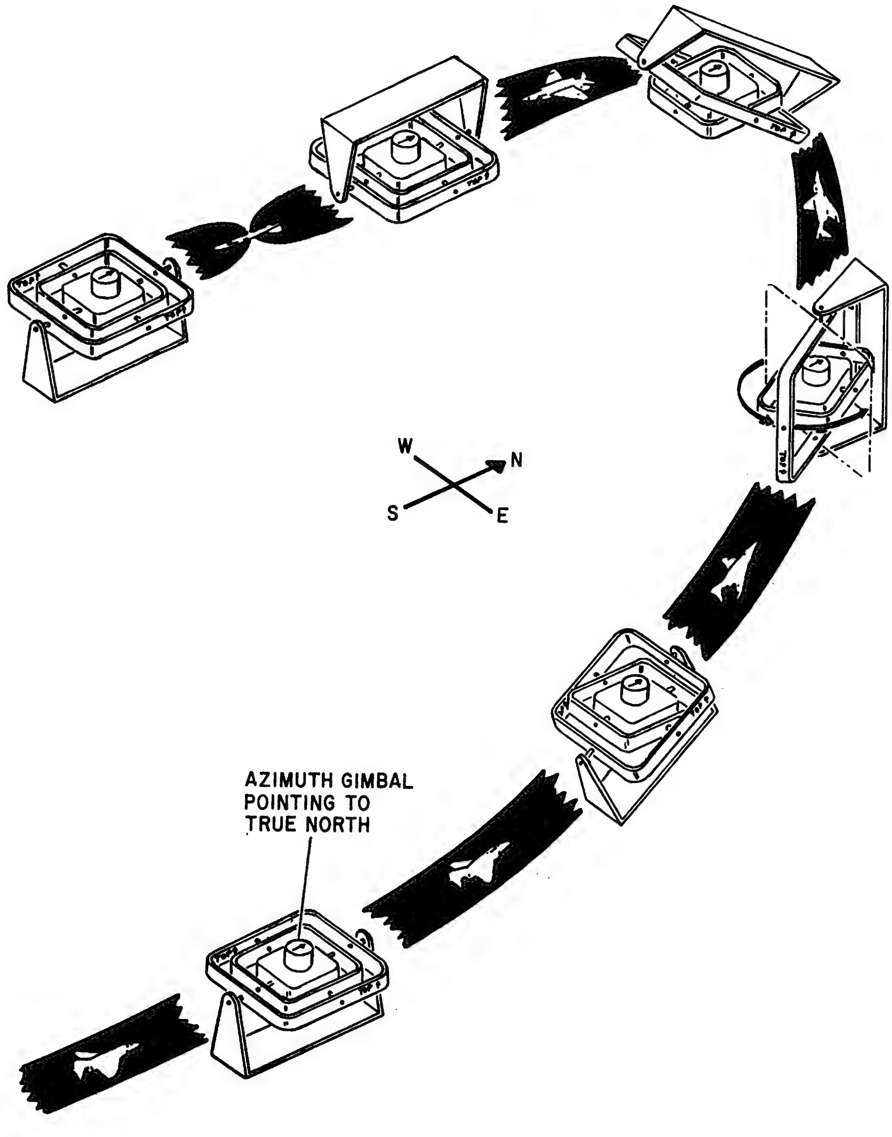

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Figure 11-12.—Gimbal flipping action.

The above formula shows that the period of a simple pendulum is proportional to the square root of the length of the suspending spring. The longer the string, the longer the period.

A property of the simple pendulum that is very useful in the construction of an inertial stable element is shown in figure 11-15. Two pendulums are suspended by strings of different lengths, and the point of suspension of each is accelerated horizontally by equal forces. The inertia of the "bob" resists the change in its state of motion, causing the "bob" to lag behind the point of suspension. This action produces an angular motion of the pendulum with respect to the local gravity vector. Figure 11-15 shows that the length of pendulum (B) is longer than pendulum (A), and that the angular motion of pendulum (B) is less than pendulum (A), for a corresponding linear motion of the suspension point. Therefore, the longer the suspending string, the less the angular motion of the pendulum for a given linear motion of the suspension point.

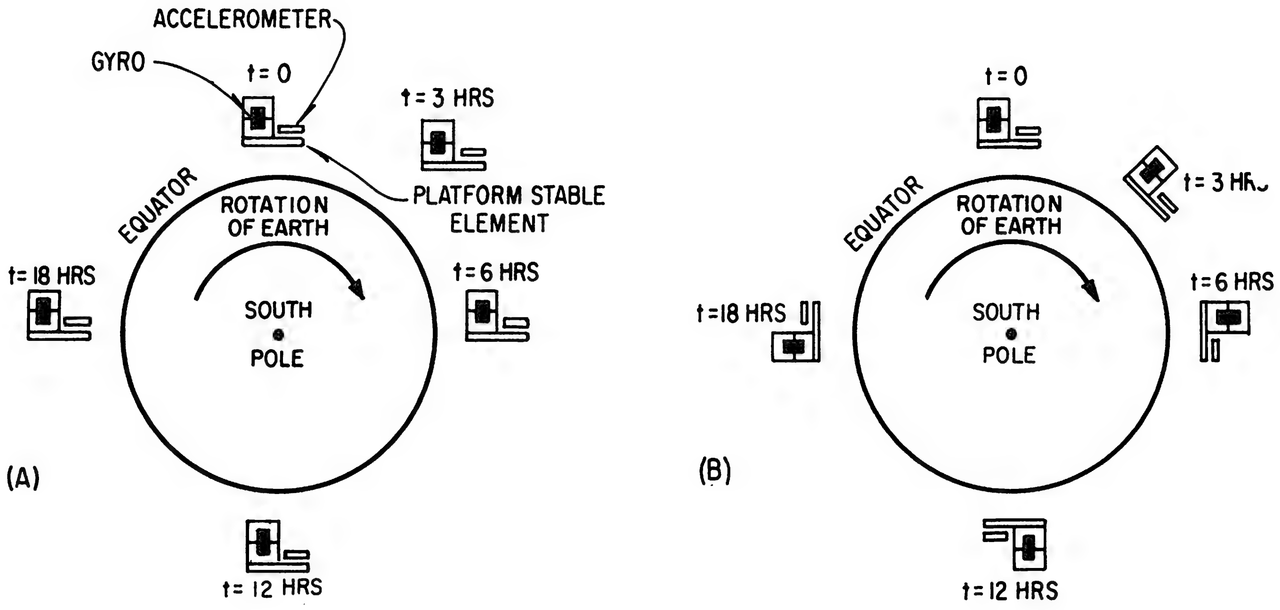

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Figure 11-13.—Earth rate torquing. (A) Without gyro torquing; (B) with gyro torquing.

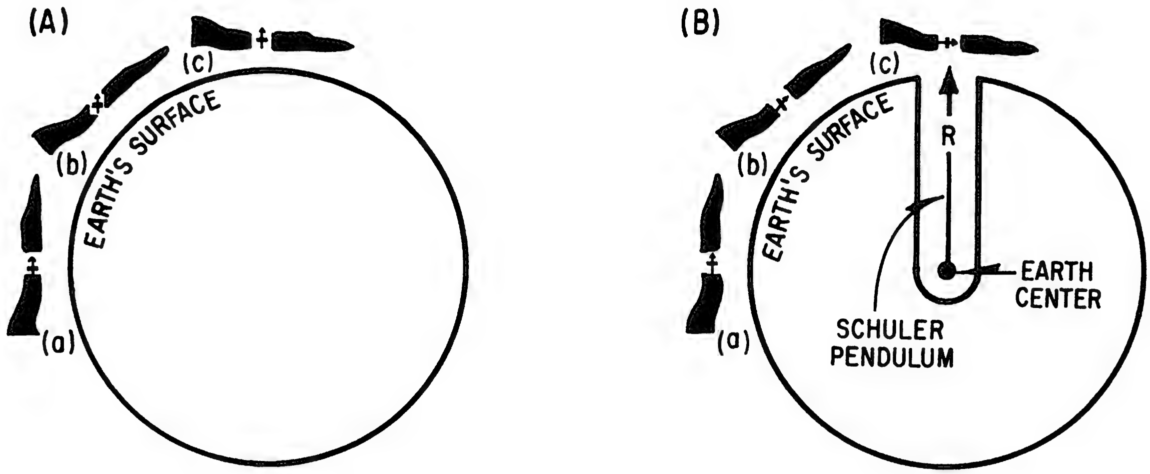

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Figure 11-14.—Aircraft rate torquing. (A) Without gyro torquing; (B) with gyro torquing.

Now, consider what would happen if the suspending string were long enough to maintain the "bob" at the center of the earth and the suspension point were transported horizontally along the earth's surface (fig. 11-14 (B)). Since the "bob" is hypothetically at the center of the earth, which is also the seat of the earth's gravity field, an acceleration of the point of suspension along the earth's surface would merely realine the suspending string with the

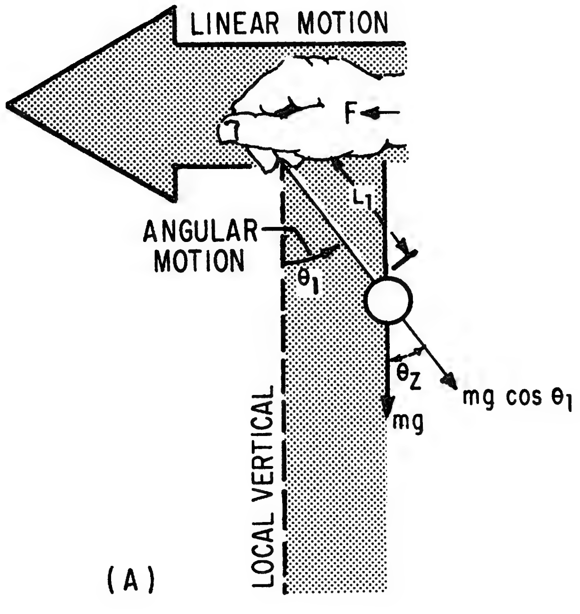

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Figure 11-15.—Simple pendulum.

new local gravity vector; therefore, the angular motion of the pendulum with respect to the gravity vector for any horizontal acceleration of the suspension point is zero. This particular pendulum is called the "Schuler pendulum," which is illustrated in figure 11-14 (B). It gets its name from the German engineer, Maximillian Schuler, who solved the problem of oscillating shipboard gyrocompasses in the early 1900's. Of course, Schuler could not use the simple pendulum itself to solve this oscillating problem, for that is obviously impossible. He used the principle of the simple pendulum to construct a pendulum that reacted like a simple pendulum whose length was equal to the radius of the earth, which is approximately 3,440 miles long and has a period of oscillation of about 84.4 minutes. Since the period of oscillation of a pendulum is proportional to the square root of its length, any pendulum constructed to oscillate with a period of 84.4 minutes would have an equivalent length of approximately 3,440 miles. Such a pendulum is the Schuler pendulum, which is a special case of the compound or "physical" pendulum. Figure 11-16 illustrates three examples of compound pendulums.

COMPOUND PENDULUM.—In figure 11-16 (A), the pivot point is farthest away from the center of gravity, which is represented by distance d; in (B), the pivot point is closer to the center of gravity than in (A), but farther away than the one shown in (C) which is pivoted at the center of gravity.

The pivot point of each pendulum shown in figure 11-16 is given the same acceleration; therefore, each pendulum possesses the same linear motion at its pivot point. Yet, each pendulum has a different angular motion. Note that, as distance d decreases, the angular motion of the pendulum with respect to the local vertical (gravity vector) decreases and distance L increases. Distance L, is the distance from pivot point P to the center of oscillation, point O. Note also, that as the pivot point and the center of gravity become closer together, the equivalent length L of the pendulum becomes longer. Figure 11-16 (C) shows the pendulum pivoted at the center of gravity, in which case there is no angular motion of the pendulum and the equivalent length L is infinite. Therefore, it is not a pendulum; it is a perfectly balanced mass which has an infinite period of oscillation. Thus, if it is possible to construct a pendulum of infinite equivalent length and period, it is also possible to construct one that has an equivalent length of 3,440 miles. Such a pendulum

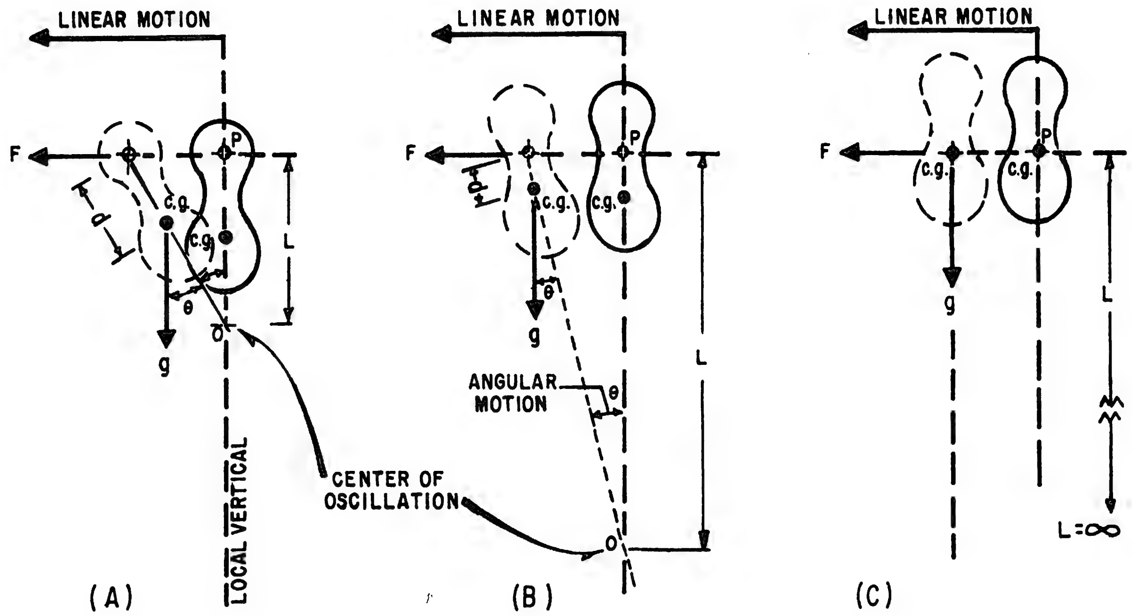

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Figure 11-16.—Compound pendulum.

would be pivoted at some distance d from the center of gravity which would be a distance greater than the one in figure 11-16 (C), but less than the one in (B). When it is pivoted at a point where the period of oscillation is found to be 84.4 minutes, the equivalent length will be approximately 3,440 miles long—hence, a Schuler pendulum.

The stable element is essentially a Schuler pendulum; however, it is not entirely mechanized by mechanical means, as was shown in the foregoing discussion on Schuler pendulums, for the earth's radius varies with latitude. The earth's radius is greater at the equator than it is at the poles. For this reason the stable element utilizes what is known as SCHULER TUNING. Schuler tuning is a process of torquing the platform to a position normal to the gravity vector by signals received from a computing loop as the stable element is transported over the earth. Schuler tuning will be discussed in more detail later in this chapter.

Frame of Reference

The frame of reference about which the inertial navigation system measures acceleration, to define the instantaneous position of the aircraft, is the conventional latitude-longitude coordinate system. In figure 11-17, notice that the geographic line (local vertical) to the center of the earth and the north pole are two prime references which may be determined anywhere on the earth's surface by the motion sensors

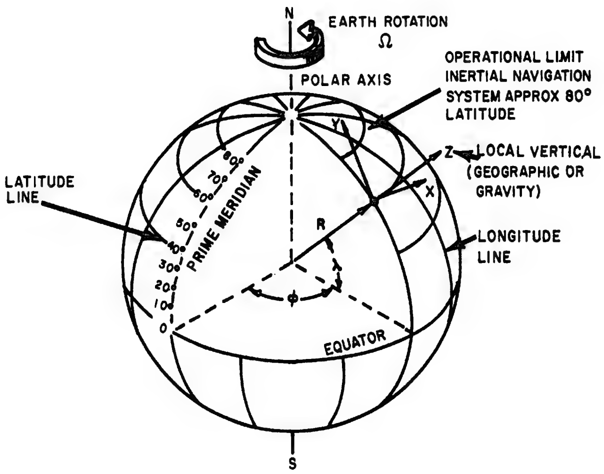

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Figure 11-17.—Frame of reference.

within the inertial navigation system. The local vertical, established and maintained by the inertial navigation system, is the gravity vertical and is coincident with the geographic vertical. The inertial navigation system is oriented to the true north reference by sensing the motion of the earth rotating on the polar axis. The frame of reference defined is horizontally alined in a plane parallel to the surface of the earth and oriented to true north.

ESTABLISHING THE REFERENCE.—It may be seen from figures 11-10 and 11-17 that, by establishing the frame of reference, that three orthogonal axes of the stable element will be alined automatically to the horizontal coordinates of the latitude-longitude navigational system; that is, the stable element Z axis is alined with the local vertical, the Y axis is alined north-south and, therefore, coincident with lines of longitude, and the X axis is alined east-west coincident with lines of latitude. In all calculations, X axis is positive east, Y axis is positive north, and Z axis is positive away from the center of the earth.

A pair of two-degree-of-freedom gyroscopes are used to establish and maintain the stable element to the frame of reference. Since a two-degree-of-freedom gyroscope has two sensitive axes, it is necessary that two such gyroscopes (fig. 11-10) be used, with the redundant upper gyroscope Z axis not utilized. They are physically mounted, on the stable element, so that their spin axes are exactly perpendicular in the horizontal plane. With this arrangement, alinement of the upper gyroscope spin axis north-south will automatically aline the lower gyroscope spin axis east-west.

The stable element containing the gyroscopes is supported by the platform gimbal system, which is a series of interlocking rings that isolate the stable element from aircraft motion and disturbing forces. Thus, the gyroscopes control the stable element. However, if a free gyroscope is initially oriented so the spin axis alines east-west in a horizontal plane, the gyro will precess in respect to the earth's surface due to the earth's rotation about its polar axis. In order to maintain an earth reference, the gyro must be torqued opposite and equal to the apparent precession. The upper (XZ_2) and lower (YZ_1) gyros are affected by the earth's rotation. Corrections for earth rotation are applied to the Y and Z_1 torquing coils (Z_1 and Z_2 are caged together and both will respond accordingly). The X torquing coil is not used for earth rate corrections.

To establish an earth frame of reference, the gyroscopes are controlled by continuously computed signals that introduce forces (torque) to cause their spin axes to precess in the desired direction. This torque is the form of direct current signals (ωx, ωy, ωz) applied to torquing coils mounted on the gyro float assembly. A magnetic field is created which aids or opposes the magnetic fields of the permanent magnets mounted on the end bells which effectively torque the gyro and cause the spin axis to precess to the desired orientation.

Establishing the frame of reference is sequenced to, first, level the stable element by alining it to the local vertical (gravity vector). This is accomplished by torquing the XZ_1 and YZ_2 gyros to move the stable element until the X and Y accelerometers cease to sense any acceleration caused by gravity; that is, the output from the accelerometers provide the torquing signals for the gyros. During this time, and at all times while operating, computed earth rate torquing signals (ωy and ωz) continuously applied to the Y and Z axes torquing coils of the lower gyro. The magnitude of these earth rate torquing signals is resolved by computing the vertical and horizontal components of earth rate as a function of latitude.

As previously shown, the upper X axis gyro is not affected by the rotation of the earth and, therefore, no compensating earth rate torquing signal is applied to this gyro. After the stable element is leveled, the X axis torquing signal, consisting of earth rate acceleration only, is now used to drive the stable element in azimuth to null this signal. At that time, the X gyro's spin axis is alined to true north and the frame of reference has been established. This alinement condition will remain until the inertial navigation system is manually sequenced to the navigate position.

MAINTAINING THE HORIZONTAL REFERENCE.—When the aircraft remains stationary or moves at a constant velocity, the accelerometer outputs are zero; but if the aircraft attitude changes while maintaining a constant speed, the accelerometers would sense an acceleration due to gravity. Since the accelerometers cannot distinguish gravitational accelerations from horizontal accelerations, the integrators would develop a fictitious velocity with a corresponding distance error. It is

essential, therefore, that the accelerometers be held in a truly horizontal reference plane that is always independent of the aircraft attitude with respect to the horizontal plane.

This is a fundamental requirement of the inertial navigation system, and the accuracy with which the horizontal reference is maintained will determine the overall performance capabilities of the system. A gyro stabilized platform mounted in a gimbal structure serves as an inertial reference and, in addition, accurately defines directional reference for the coordinate system.

With the platform installed in the aircraft and alined along the Y axis, it will remain level regardless of aircraft attitude. The instant the aircraft begins to change attitude, for example in pitch (fig. 11-18), the platform gyro senses this angular movement and begins to precess at a rate proportional to the pitching rate. A pick-off coil on the gyro axis senses this movement, thus changing it to a voltage, which is amplified and fed into the pitch gimbal servo drive motor. The motor rotates the stable element exactly equal and opposite to the aircraft angular motion. As a result, it continuously precesses the gyro to its neutral or level position, thus maintaining its output signal at null.

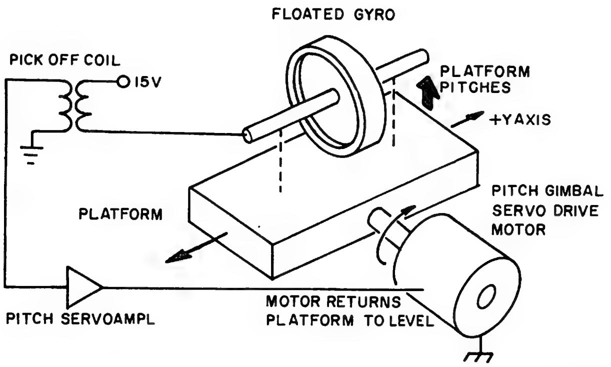

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Figure 11-18.—Gyro maintaining inertial platform level.

Regardless of any new pitch attitude the aircraft assumes, the gyro will keep the stable element level, since this is the only position which allows its output signal to be at null. In actual practice, the stable element is maintained level and is also alined in azimuth by a similar method in yaw and roll. This is necessary so that the sensitive axis of the north-south accelerometer is alined true north-south and the east-west accelerometer is alined true east-west. The stable element is then accurately alined to the three coordinates: north (Y axis), east (X axis), and up or true vertical (Z axis). This arrangement allows the accelerometers to accurately detect aircraft motion.

MAINTAINING THE VERTICAL REFERENCE.—The stable element must remain perfectly level or the accelerometers will sense a false acceleration due to a component of the earth's gravity. Since the gyros try to maintain their inertial position in space and not with respect to the local vertical, this causes the stable element to drift off level as the aircraft moves over the curvature of the earth (fig. 11-14). This situation would allow a buildup of very large errors in velocity and distance. This condition develops whether or not the aircraft is moving over the earth's surface, because the earth's rotation alone will develop the same type of errors.

The stable element must always be perpendicular to the local vertical or, in other words, the gyros must be caused to precess in such a manner so as to maintain the stable element level, as the aircraft moves, with respect to the center of the earth. In this way the sensitive axis of the accelerometers would be maintained horizontal to the earth at all times and respond only to the horizontal component of acceleration.

MAINTAINING THE FRAME OF REFERENCE.—Accuracy in maintaining the stable element to the frame of reference determines the overall performance capabilities of the system. Gyro torquing rate signals are continuously computed to maintain the frame of reference. After alinement, the inertial navigation system is manually sequenced to its operating condition (navigate); and if the aircraft were to remain stationary, the gyro torquing rate signals would consist of earth rate only. However, as the aircraft moves over the curvature of the earth, the stable element earth reference would be lost as the gyros precessed due to vehicle movement, as shown in figures 11-13 and 11-14. Therefore, additional gyro torquing signals are continuously computed within the inertial navigation system to compensate for the vehicle's movement. They are aircraft rate torquing signals and depend on the velocity of the aircraft in respect to the frame of reference; that is, east-west velocity and north-south velocity. The angular rate (ω) is

directly proportional to the velocity of the aircraft along the periphery of the earth. Aircraft rate torquing is applied to both gyros so that they will precess about all three axes (X,Y,Z) to continuously maintain the frame of reference.

Deriving Velocity and Distance

The inertial navigation system is capable of accurately detecting acceleration of the aircraft, and with the use of precision integrators, determine aircraft velocity and measure distance traveled. Accelerations are measured in units of ft/sec^2 by the accelerometers; but for analog computation, the accelerations are developed in volts per g of accelerating force. The velocity integrator integrates the accelerating force to obtain velocity; the distance integrator integrates velocity to obtain the distance traveled.

There are two velocity integrators in the system to obtain V_x and V_y along the two horizontal axes and two distance integrators to obtain distance traveled along the two horizontal axes. In addition, some inertial navigation systems employ one other velocity integrator to obtain V_z along the vertical axis.

Accelerometer Output Corrections

The arrangement of the accelerometers with their sensitive axes horizontal and perpendicular to one another is perfectly suited to navigation over a stationary plane or over flat terrain moving at uniform speed in a straight line. The earth, however, is a rotating sphere and, insofar as the inertial platform is concerned, only points along the equator can be considered to possess uniform linear motion. Here, and only here, the accelerometer signals can be translated directly into position information. Since very few flights are carried out exactly along the equator, it is necessary to provide an automatic device that will alter the accelerometer signals so that the system reports meaningful information. The corrective device is purely electrical. All or part of the circuitry is active whenever a velocity signal voltage is present anywhere north or south of the equator. These circuits utilize the velocity signals, modified according to the latitude of the aircraft position, to insert artificial acceleration signals to those already in the accelerometer output circuits.

The circuits are divided logically—some are devoted to centripetal effect, some to Coriolis. It should be noted, however, that the corrections are complementary.

Although it is convenient to assign a separate purpose to the circuits, as we have in the following discussions, the functions overlap, and it is not entirely accurate to consider them separate entities.

CENTRIPETAL CORRECTION.—Centripetal correction differs from that of the Coriolis correction in that it has no relationship to earth dynamics. If the earth were stationary, it would still be necessary to insert centripetal correction voltages to the accelerometer signals to obtain an accurate plot of any course that does not exactly coincide with one of the earth's coordinate great circle routes; that is, an exact polar or an exact equatorial orbit. On a great circle route, a route that ultimately circles the earth center, every linear acceleration initiates motion; but unless the route is due north-south or directly along the equator, the system is incapable of plotting it accurately from the "raw" accelerometer signals.

The orbit resulting from linear acceleration, and the logic of applying centripetal corrections to obtain an accurate plot of track, can be understood if one considers any simple circumstance involving a single acceleration and the inertial reaction. For example, if a perfect bowling lane were built completely around the earth at the equator, a bowler could theoretically stand behind the pins, roll the ball in the opposite direction, and (after a few years' time) get a perfect strike on the head pin. Buf if the lane were built on latitude 10°N, the ball would invariably veer south; and after a few thousand yards would fall into the right-hand gutter if rolled east or into the left-hand gutter if thrown west—in both cases, the south gutter. The reason for this phenomenon is evident in the consideration of a lane built on a latitude in the Arctic only a few yards from the pole. Here the curve of the lane is obvious, and it is readily apparent that if the ball is accelerated due east it will in fact follow, in inertial space, a straight course that intersects the outside gutter. If the ball is to roll at uniform speed and remain in the alley, a uniform north acceleration force must be exerted on the ball in transit. Note that in this case the north acceleration is a corrective force and does not produce north velocity with respect to the alley.

As illustrated in figure 11-19, a north-south accelerometer aboard an aircraft circling the pole finds the same phenomenon. In a

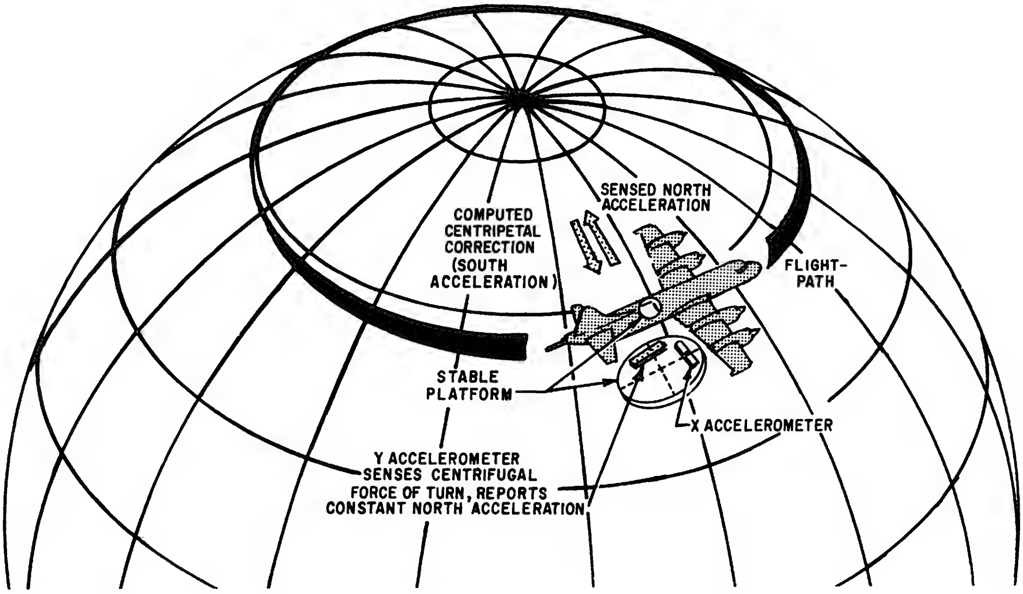

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Figure 11-19.—Centripetal correction along latitude.

steep-banked turn, the centrifugal force tends to deflect the north-south accelerometer. It blindly reports a steady north acceleration, and a growing north velocity is recorded when, in fact only east velocity exists.

The fault does not lie in the accelerometers but in the nonlinear pattern of the accepted geographic coordinate system to which the platform is slaved. The coincidence of earth axis and pole seems to imply earth dynamics in the phenomenon, but actually this is not a factor. If the coordinate systems were shifted to place the pole at New York and New York were used as the focal point of one accelerometer axis of an inertial navigator circling the city, the accelerometer sensitive to this axis would report acceleration toward it.

In a spherical coordinate system, any linear vehicle acceleration that initially affects both accelerometers will NEVER result in the vehicle's reaching the pole. The vehicle will follow a great circle track that first approaches one of the poles, will fly due east or west for a brief period, and will then depart the pole as shown in figure 11-20.

Although the velocity resulting from any given acceleration is initially computed correctly with respect to space, the direction of the speed must be constantly altered if the navigational system is to accurately report a great circle course that crosses both latitude and longitude. On such a course, the aircraft does not turn as it does following a line of latitude, and consequently it does not generate uniformly false north acceleration signals. The centripetal correction circuit does, however, continue to "plant" signals of acceleration toward the equator. This has the effect of altering the reported speed (the result of velocity along both axes); and since no actual acceleration has taken place to cause a speed change, it is apparent that the centripetal correction circuit must simultaneously plant a positive acceleration in one axis if it plants a negative acceleration in the other. Therefore, when a portion of the north or south velocity is canceled, the system must add a sufficient increment of east or west acceleration to allow the reported total speed to be unchanged while the reported direction of flight is "bent" toward the equator. As shown in figure 11-20, after a single north-east acceleration has occurred, the north vector becomes progressively shorter. Note that the resultant speed vector is always of the same magnitude.

In summation, it can be said that an east or west acceleration in either hemisphere contains a "hidden" element of acceleration toward the equator, and the centripetal correction simply acts to reveal this element. If the aircraft

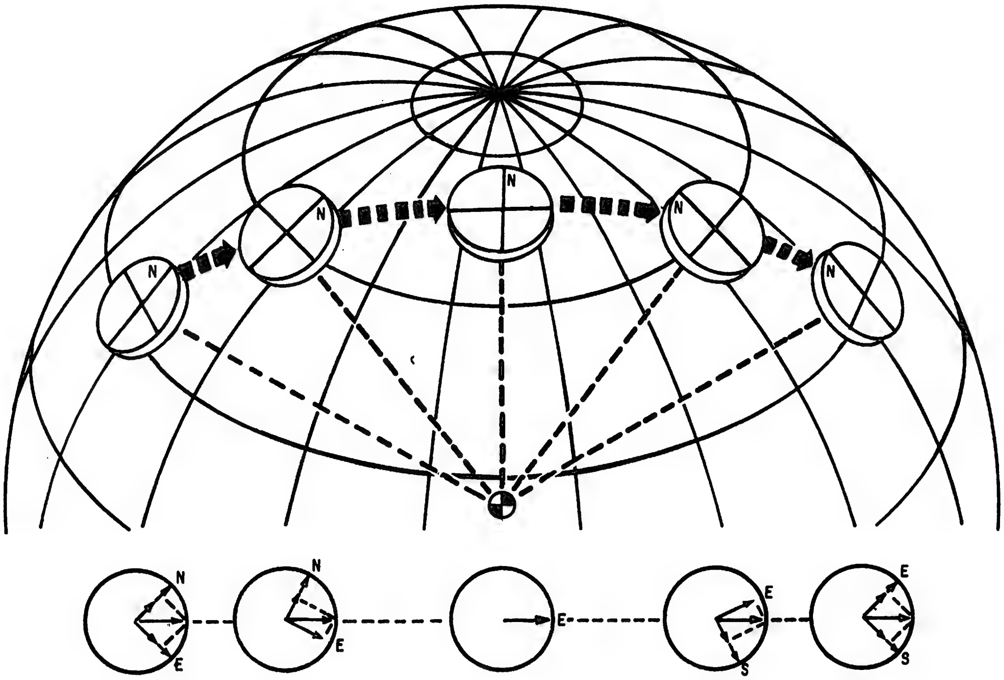

Figure 11-20.—Platform on great circle route.

velocity is anything but due north or south, in the northern hemisphere the centripetal correction "manufactures" a south velocity component. In the southern hemisphere, it manufactures a north component.

CORIOLIS CORRECTION.—As mentioned previously, the scope of the centripetal correction, limited to transmitting the effect of linear acceleration to the resulting track over a sphere, makes no allowance for earth dynamics. Since the earth rotates toward the east, all points on the surface possess a constant radial velocity that is maximum along the equator and progressively less at higher latitudes.

Although it is true that the earth has a trajectory in space, this motion is of no importance to the inertial navigation system because it is shared by every point on the sphere. The only variable involved is the variation in the earth's tangential velocity at different latitudes. While the accelerometers do not automatically make allowance for this variation, it must be taken into account.

The need for such an allowance is graphically illustrated in an example in which an inertial navigator, totally devoid of any Coriolis corrective mechanism, is put aboard a train in the northern hemisphere, alined, and transported north. If it is assumed that the train is located at a latitude at which the earth's tangential velocity is 800 knots east during the alinement, it is obvious that the train's eastward velocity must be constantly reduced as it progresses north. This is the same thing as saying that an acceleration is occurring.

Since the train is constrained by the track, a force from the east will be exerted on the wheel flanges. This force is sensed by the east-west accelerometer as acceleration to the west, and a growing west velocity is computed. As indicated by figure 11-21, an aircraft flying north directly along a moving longitude meridian will subject the east-west accelerometer to this same force as its courses in space is altered to the left to compensate for the decreasing eastward velocity of the earth's surface.

If either vehicle (train or aircraft) travels north and stops at a latitude where the earth's tangential velocity is 200 knots less than the tangential velocity at the point of its initial alinement, the velocity computer will continue

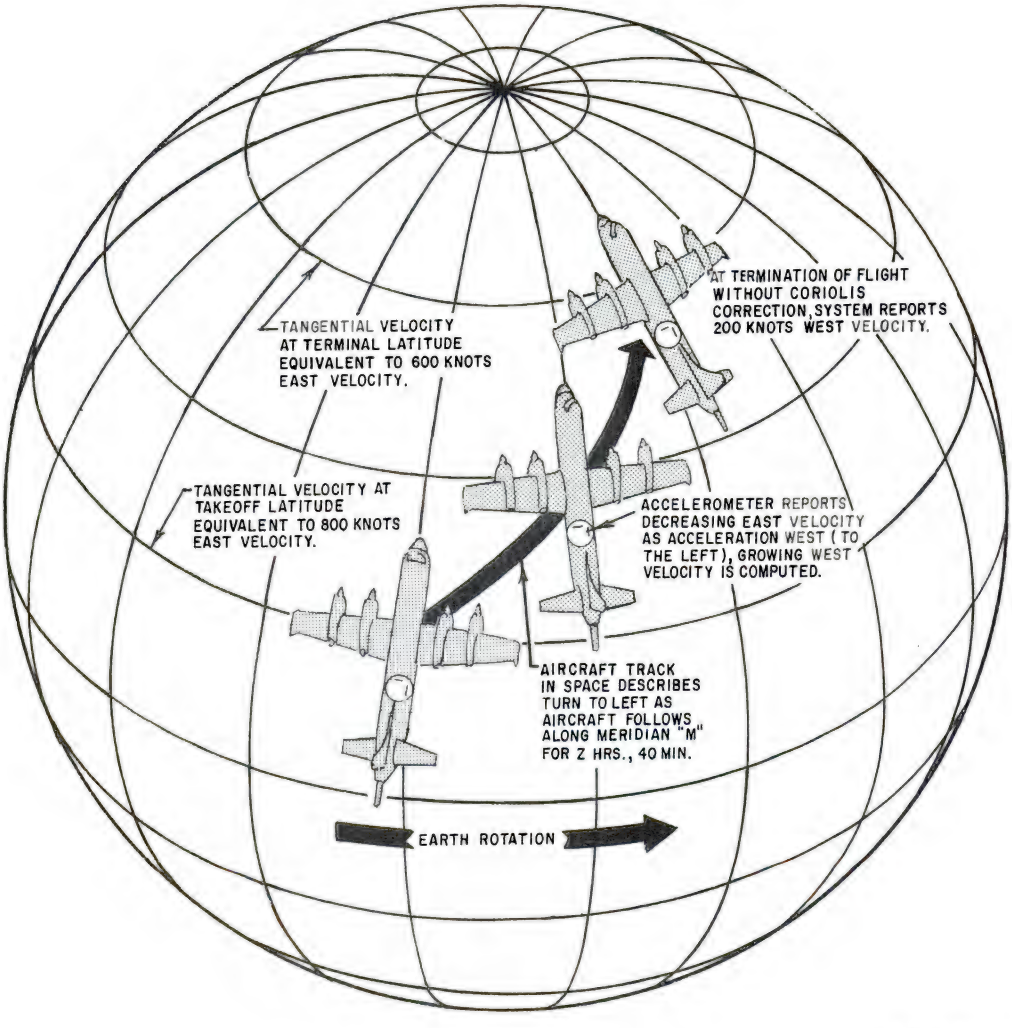

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Figure 11-21.—Coriolis effects.

to report that the vehicle is traveling west at 200 knots even though it is perfectly static.

The Coriolis correction prevents this circumstance from occurring by creating exactly enough east acceleration signal to offset the continual west acceleration signal generated by the east-west accelerometer as it travels north. The east and west accelerations cancel, and no change in longitude is reported. Of course, if the aircraft makes the return trip, the platform begins the trip under the delusion that 600 knots east is zero velocity and, as it travels south, the increasing earth tangential velocity causes it to constantly report east acceleration. In this case, the Coriolis correction also reverses; that is, it manufactures a west acceleration that exactly voids the east acceleration.

Note that in both the foregoing cases, the Coriolis correction has supplied an artificial signal of acceleration to the right side of the actual track. This is the nature of the Coriolis correction, regardless of the direction of travel in the northern hemisphere. When the track is due east along a latitude line, as illustrated in figure 11-22, the centripetal correction offsets the increment of north acceleration generated by the aircraft speed; the Coriolis correction accounts for the additional force generated by earth rotation. For example, if the earth's tangential velocity at latitude "L" is assumed to

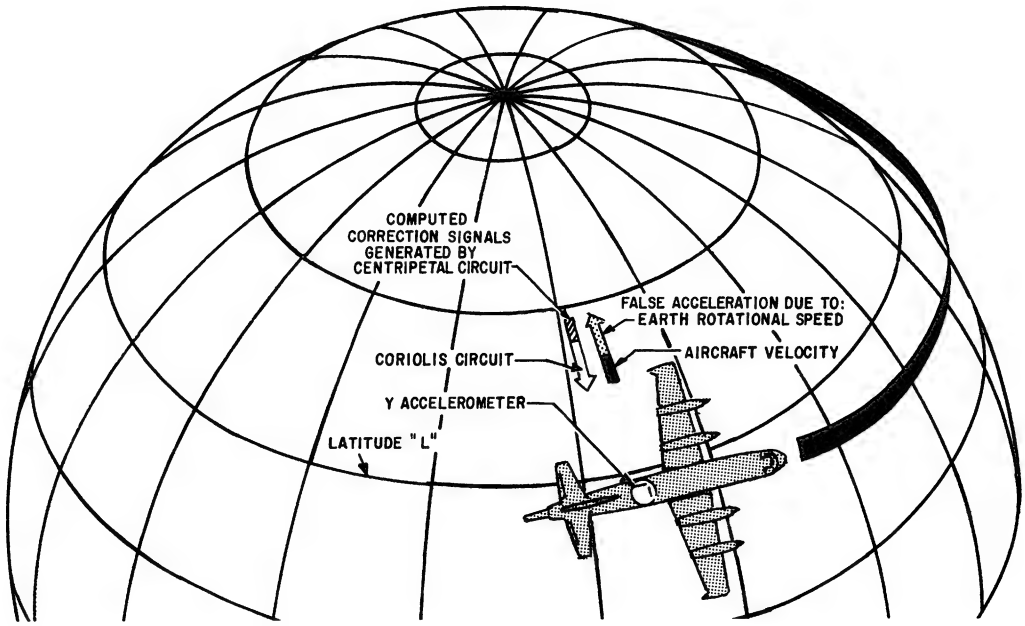

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Figure 11-22.—Coriolis and centripetal corrections.

be 700 knots and aircraft speed is 350 knots, it is obvious that the total speed is 1,050 knots. Centripetal correction offsets the acceleration caused by the centrifugal force of a 350-knot turn of this radius; Coriolis correction offsets the force of a 700-knot turn. In this case, the two corrections are summed.

If the course is reversed and the plane flies west, the corrections become opposite in polarity—the centripetal signal is still south, but Coriolis is north (to the right of the track)—and therefore only a part of the larger correction is effective.

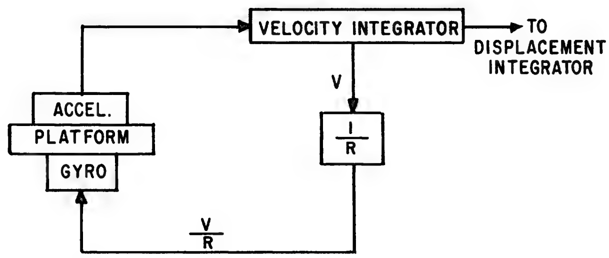

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Figure 11-23.—Simplified Schuler tuned loop, platform level.

Schuler Tuned Loop

The Schuler tuned loop is a closed loop circuit between the accelerometer, velocity integrator, and stable element that is designed to prevent enormous velocity and distance errors owing to misalinement of the stable element. Figure 11-23 illustrates a simplified Schuler tuned loop with the platform alined.

The output of the accelerometer is integrated to provide a velocity signal. The velocity signal is multiplied by 1/R, where R is equal to the earth's radius, thus deriving an angular velocity about the earth's surface, V/R. This angular velocity is then used to torque an integrating gyro and cause the platform to precess about the earth's surface at the same rate that it is being transported over the surface, thereby maintaining the platform normal to the local vertical.

There are two such loops in an inertial navigation system, one for the north and the other for the east. The accelerometer in the north loop senses north-south accelerations, yet the gyro in the north loop senses east-west angular rates—the vehicle's angular movements about the east-west axis.

By convention, accelerometers and gyros are named according to the direction of their

sensitive or input axis, and the inertial or Schuler loop takes the name of its accelerometer. The north loop contains the north accelerometer and the east gyro, while the east loop contains the east accelerometer and the north gyro.

With the platform initially unlevel, as shown in figure 11-24, the accelerometer will sense a component of gravity, g sin θ. This signal would then be integrated, resulting in the velocity signal $V\theta$. The velocity signal would then cause the gyro to precess in a clockwise direction. When the accelerometer is positioned so as to sense zero gravity, the velocity output would continue to torque the platform in a clockwise direction, causing the accelerometer to now sense a gravity component of the opposite polarity. This signal will now cause the velocity signal to decrease to zero and then to build up in the opposite direction and precess the platform in a counterclockwise direction. The period of oscillation set up by this mechanization has a period of 84 minutes or equal to that of the Schuler pendulum. Figure 11-25 shows the buildup and decay of acceleration and velocity errors as a result of such errors as just described.

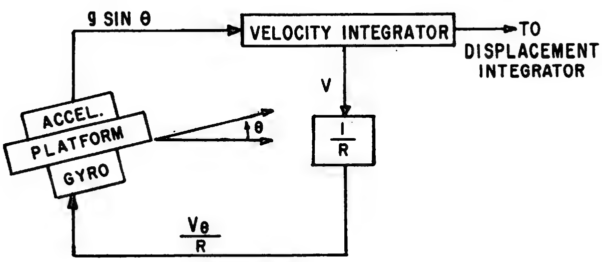

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Figure 11-24.—Simplified Schuler loop, platform unlevel.

ALINEMENT

As has been said before, inertial navigation depends on integration of acceleration to obtain velocity and position. In any integration process, the initial conditions must first be known, which in this case are velocity and position. The accuracy to which the navigation problem is solved depends greatly upon the accuracy of the initial conditions. Therefore, system alinement is of paramount importance.

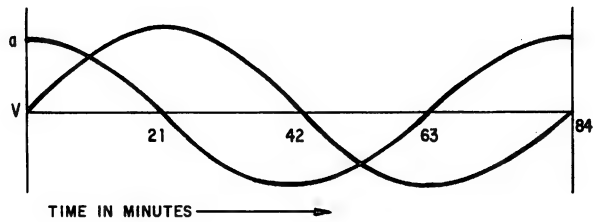

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Figure 11-25.—Schuler tuning—acceleration errors vs velocity errors.

Basically, system alinement consists of creating a coincidence between the platform axes and the computer axes. This can be done by rotating either or both systems. There are two general methods of accomplishing this condition: (1) The system is slaved to an external reference source, or (2) the system may have the built-in capability to sense misalinement and correct itself. Of course, combinations of both these methods can be, and often are, used.

External references take three basic forms: terrestrial, celestial, and inertial. The terrestrial system uses surveyed lines, benchmarks, plumb bobs, and bubble levels. These methods result in level accuracies of about 10 seconds of arc and heading accuracies to 3 minutes of arc. Celestial information is usually obtained from star trackers and radio sextants with accuracies to 10 seconds of arc. When an inertial system is used as a source, the accuracies are dependent upon its initial source and of course the length of time since it was last alined. Such a method is usually used for mobile alinement where primary sources cannot be used.

The use of an external reference system requires transfer devices to transmit the reference information to the system. The transfer devices take the form of optical or electromechanical. Optical devices include theodolites and autocollimators; the electromechanical devices are synchro-resolver or digital type. Optical methods are able to produce accuracies of a few seconds of arc, but the electromechanical methods are only good to about 30 seconds of arc.

In self alinement, the inertial sensing instruments mounted on the platform sense the deviation from the desired position. In order to determine the orientation of a three-axes

orthogonal coordinate system, it is necessary to have at least two noncollinear (not parallel) reference vectors. For self alinement, the earth's spin vector and the mass attraction gravity vector serve this purpose. The self alinement puts less requirements on the computer, because the accelerometer outputs do not have to be resolved into components of gravity and vehicle acceleration. If the accelerometers and gyros are mounted on the same element, then their relative position can be fixed and does not have to be computed.

Self alinement is often divided into two modes: (1) Rough or coarse alinement (sometimes called caging), and (2) fine alinement. Fine alinement itself is divided into two modes, leveling and gyro compassing.

Rough Alinement

The purpose of rough alinement is to provide a convenient starting point for the later phases of alinement. In most cases, the gimbals are slaved to their own synchro outputs or to some external source which has a particular orientation with respect to the vehicle. The duration of rough alinement is controlled by a timing network and in most cases is approximately one-half minute long.

Fine Alinement (Leveling)

Fine alinement or leveling is accomplished by rotating the platform axes to the computer axes. For a locally level system, this would be done by placing the X and Y accelerometer axes mutually orthogonal to the gravity vector. Since the accelerometers are mounted at right angles, a motion about one axis will cause the other to go through an angle with respect to the gravity vector. Therefore, by connecting the output of an accelerometer in such a way as to torque about its orthogonal axis, it can slew itself to a null position—where it senses no component of gravity. As pointed out earlier, the device which can be torqued about an axis is a gyro. In this case, the gyro which is torqued is the one sensitive about the axis orthogonal to the accelerometer being leveled; that is, the Y (north) gyro torques the X (east) accelerometer to level, etc.

The accelerometer will provide a d-c voltage that is proportional to the sine of the off level angle. In the leveling mode this voltage is amplified and applied to the gyro whose sensitive axis is perpendicular to the sensitive axis of the accelerometer. (See fig. 11-26.) In other words, the output of the X accelerometer is applied to the Y gyro and the output of the Y accelerometer is applied to the X gyro.

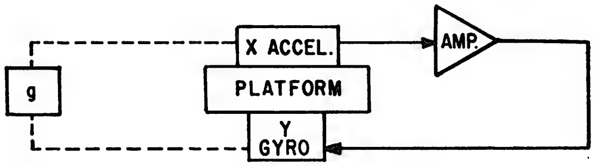

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Figure 11-26.—Typical leveling loop.

If this network is repeated for the Y accelerometer and the X gyro loop, we now have a means of establishing a plane which is perpendicular to the gravity vector. Hence, this portion of the alinement has established a fixed relationship between the platform and one of the two reference vectors. Although the level plane is established, the entire position of the platform is not known until the angle of a vector lying in the plane with a second reference vector is known. This is done by gyrocompassing. Again the operation can be accomplished by rotating the platform axes or the computer axes. With a north pointing system, it is necessary to rotate the platform axes.

Gyrocompassing

As previously mentioned, any gyro which does not have its spin axis parallel to the earth's spin axis will apparently precess with respect to the earth. The rate at which it precesses is proportioned to the angle between its spin axis and earth's spin axis. This angle can be resolved into two components. Since the gyro spin axis lies in the level plane previously established, one component can be found which is in the plane itself. Now we only need to find the angle between the spin axis and a vector in the level plane which intersects the earth's spin vector. After these two angles have been found, we can say that we know the exact position of the platform axis.

It is readily seen that the rate at which the gyro in question appears to precess is equal to $\Omega \cos \lambda \sin \alpha$ where

Ω = the earth's rate of rotation
λ = latitude
α = the angle the platform makes with true north

Now the spin axis of this gyro can either be torqued to a place where this term goes to zero ($\alpha = 0$) or a torquing term can be developed in the computer equal to this and then apply it to the gyro. In either case, the position of platform will be know. Figure 11-27 shows a typical heading alinement loop.

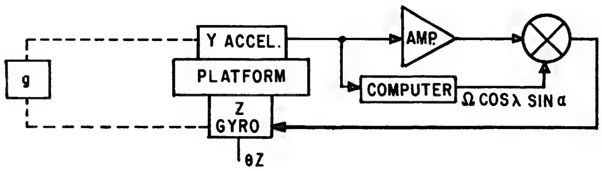

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Figure 11-27.—Typical heading alinement loop.

In a north seeking platform, the earth's rotation is utilized to aline the platform to true north. This is accomplished by using the output of the Y accelerometer and applying it to the torquing coils of the Z (azimuth) and the X (east) gyros. At the beginning of the gyrocompass phase (after the platform is leveled), the stable element is torqued in azimuth to null out the residual east gyro torquing rate. If, at this time, the stable element is not alined to true north, it will tilt due to precession of the gyros. The stable element deviation from the level position is sensed by the Y accelerometer because of gravity. The output of the accelerometer is then used to torque the X gyro until the stable element is leveled and, at the same time, to torque the Z gyro in azimuth. The process continues until the stable element is alined to true north.

Once the platform is alined, the system is switched from the alinement phase to the navigation phase of operation. In the navigation phase, the stable element would maintain an orientation with reference to free space if it were not for corrections supplied by the computer. The computer maintains the stable element level with respect to the earth and oriented to true north. If not, the accelerometers sense gravity in addition to movement of the aircraft. Coriolis, centripetal, and earth rate corrections are computed and used to hold the stable element level and alined to true north. In the navigation phase of operation, the orientation to true north is dependent on the original alined position and the computed corrections.

Alinement at Sea

The problems that arise in alining an aircraft inertial navigation system at sea are much more complex than alinement on a fixed earth base, even though our inertial reference is another inertial navigation system of very high accuracy, which is available aboard aircraft carriers. The inertial navigation reference system aboard aircraft carriers are the Ships Aircraft Inertial Navigation Alignment Console (SAISAC) and the Relative Velocity Computer (RVC). Even though there are outlets on the flight deck that make it convenient to pipe the ships inertial navigation reference information into the aircraft inertial navigation system, one major problem still remains which makes proper alinement difficult. The accelerations experienced by the ship's inertial navigation accelerometers located below decks and remote from the aircraft are not the same accelerations experienced by accelerometers in the aircraft's inertial navigation system located on the flight deck.

COARSE SEA ALINEMENT.—During coarse sea alinement, the best available true heading is derived from the SAISAC and the RVC. Aircraft carrier true heading is supplied to the RVC where a manually selected aircraft heading angle with respect to the aircraft carrier is inserted. The combined signals are then supplied to the heading computer in the aircraft's inertial navigation system, thus concluding the coarse sea alinement.

FINE SEA ALINEMENT.—During fine sea alinement, the accelerometers sense the aircraft carrier movement in addition to gravity. Since only the gravity component is used in the leveling, the accelerometer output caused by the aircraft carrier movement is cancelled by continuously computed corrections supplied by the SAISAC and RVC. The accelerometer error signals are integrated to supply a velocity. The reference velocity supplied by the RVC during sea alinement, which is actual aircraft velocity, is subtracted from the accelerometer derived velocity. The difference corresponds to the gravity component sensed by the accelerometer. It is amplified and applied to the

torquing coils of the gyros. The gyro pickoff signals are processed to cause the gimbals to rotate and cancel the pickoff error signals. The stable element is torqued until the accelerometers indicate a null or level condition.

TYPES OF INERTIAL NAVIGATION SYSTEMS

Basically, inertial navigation systems can be classified under two broad types: pure and hybrid.

The types of pure inertial navigation systems are analytic, semianalytica, geometric, and strap-down.

The types of hybrid inertial navigation systems are radio inertial, Doppler inertial, and stellar inertial.

PURE INERTIAL NAVIGATION SYSTEMS

Analytic Inertial Navigation System

The analytic inertial navigation system utilizes a platform with a fixed angular reference to some point in inertial space. No attempt is made to force the accelerometer input axes into a preferred alinement with respect to the earth. This method does not require gyro torquing and, as a result, the platform is subjected to errors of gyro drift only.

Because the platform remains rigid in space and rotates about the earth, the output accelerations become complex. They essentially consist of two major accelerations—the actual acceleration of the vehicle, and the gravitational acceleration of the earth. For navigation purposes only the aircraft accelerations are required and wanted; therefore, the gravitational accelerations must be canceled out. Yet, this cancellation is difficult to obtain because the earth's gravitational acceleration is not uniform and therefore an enormous amount of data must be stored in the computer to effect this cancellation.

The significant disadvantages of the analytic inertial navigation system are the result of maintaining the accelerometers referenced to a fixed point in inertial space. As the stable element is transported about the earth, the accelerometers are required to sense not only aircraft acceleration, but the component of the earth's gravitational field as well. The accelerometers required for this system must have a wide dynamic range as well as a high overall accuracy. The most serious problem, however, is the cancellation of the gravitational accelerations. Irregularities in the earth's shape and mass cause variations in the gravitational field; therefore, the cancellation of these variations requires a complex computer with a very large storage capacity.

Semianalytic Inertial Navigation System

The semianalytic system is the most common inertial navigation system in use today. All naval aircraft that presently use inertial navigation systems use this type either as a pure system or in conjunction with another navigation system as a hybrid system. The chief advantage of this system is that the platform gimbal structure is simple, and the computer functions are easily mechanized by either analog or digital means.

The semianalytic inertial navigation system maintains the stable element normal to the earth's gravitational vector at all times, as was discussed previously in this chapter. In this inertial navigation system, the computer converts the output accelerations of the stable element to angular velocities. These angular velocities are then used to torque the platform gyros and maintain the platform normal to the earth's gravity vector.

To prevent the platform from precessing off level due to the earth's rotation about its polar axis, the computer also develops signals equal to the angular velocity of earth resolved into the system axes and applies them to the gyro torquers. A typical simplified block diagram of a semianalytic inertial navigation system is shown in figure 11-28.

In a semianalytic inertial system, the platform is alined normal to the gravity vector, and it may or may not be alined to true north. The output of the north accelerometer is sent to an integrator where it is summed with acceleration correction terms to derive a true vehicular acceleration over the earth's surface. This acceleration signal is then integrated with respect to time deriving the north velocity component of the vehicles track. Through scaling, the velocity term is converted to an angular velocity and integrated to provide a position readout in the form of latitude. In addition, the north angular velocity is used in the latitude function generator to develop accelerometer

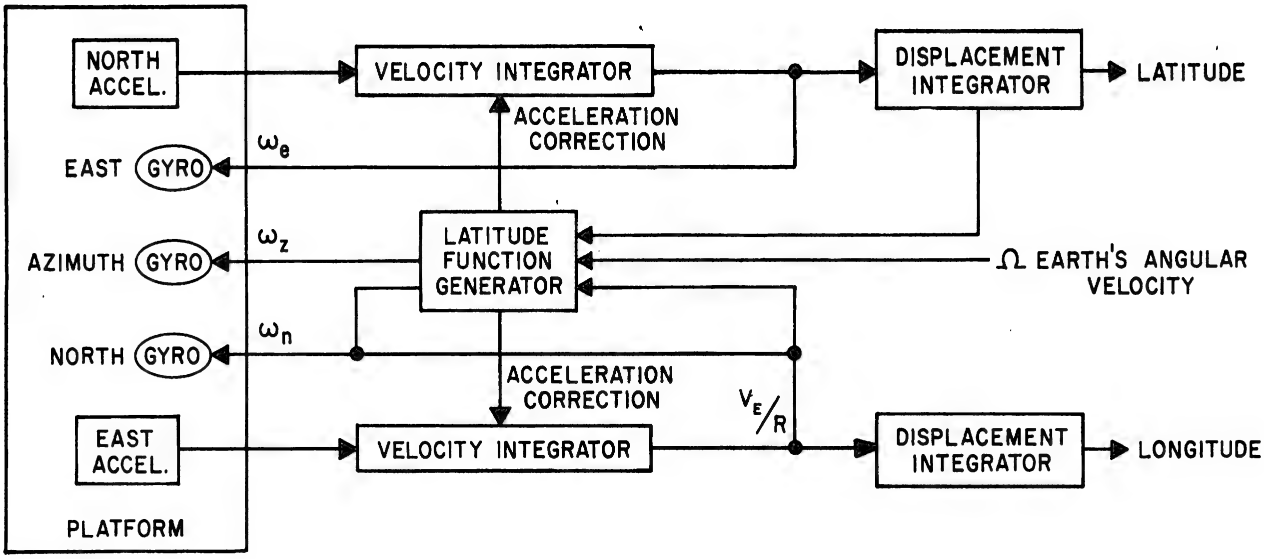

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Figure 11-28.—Typical semianalytic inertial navigation system, block diagram.

correction terms and a gyro torquing signal for the east gyro.

The output of the east accelerometer is summed with accelerometer correction terms and integrated to provide an east component of the vehicle's track. Through scaling, the velocity signal is converted to an angular velocity and is sent to the latitude function generator where it is used to develop accelerometer correction terms and torquing signals for the north gyro and the azimuth gyro. In addition, the angular velocity is integrated to develop a position readout in the form of longitude.

Geometric Inertial Navigation System

The geometric inertial navigation system utilizes a gyro system which, as in the analytic system, is referenced to inertial space in nonrotating plane. The accelerometers, however, are mounted on a gimbal structure in such a manner as to remain normal to the earth's gravitational field.

Figure 11-29 shows the relationship of the accelerometers and gyros as the platform moves over the surface of the earth. When the platform is alined at the equator and is then moved north, the gyros maintain their position in inertial space. The accelerometers remain in a plane tangent to the earth's surface at all times.

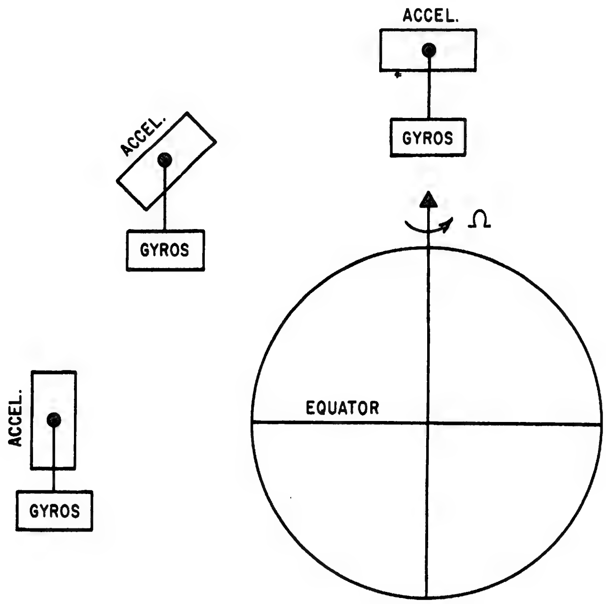

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Figure 11-29.—Transport of the geometric system's stable element.

The main advantage of this system is that the gyros are not torqued. Therefore, scaling of the gyros is not critical.

The major disadvantage is economy. The cost of mechanizing the system requires a high degree of accuracy in positioning the latitude and longitude gimbals. The semianalytic system requires much less precision to achieve similar accuracy.

Strap-Down Inertial Navigation System

In the strap-down inertial navigation system, the gyros and accelerometers are mounted directly to the frame of the vehicle. Its principal use is in ballistic missiles and spacecraft. However, this type of system can be mechanized for use in aircraft, but the present state of technology makes it more feasible to use one of the other type systems for aircraft use.

The strap-down system requires complex digital computers; analog computers are not accurate enough for use in this system.

The computer in the strap-down system replaces the gimbal structure just as the gimbal structure replaced the physical length of the Schuler pendulum. Figure 11-30 shows a simplified block diagram of a strap-down inertial navigation system.

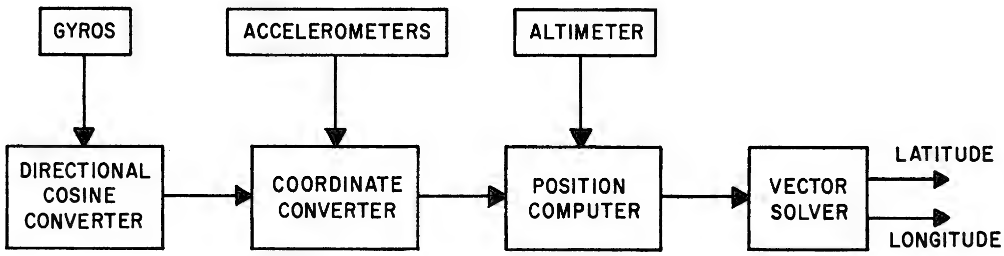

Figure 11-30.—Strap-down inertial navigation system.

In the strap-down system, the gyros provide angular rates which are then converted to directional cosines (i.e., space vectors). These signals are used to determine the attitude of the vehicle with respect to an inertial frame of reference. The coordinate converter utilizing inputs from the accelerometers and the directional cosine converter determine accelerations along the inertial reference axes. The position converter accepts inertial acceleration and altitude information to develop Cartesian coordinates representing the vehicle's position in inertial space. These vectors are then sent to the vector solver where they are summed to provide readouts of latitude and longitude.

Alinement of the strap-down system is accomplished by supplying the directional cosines of the vehicle frame with respect to a desired inertial reference to the computer. No physical orientation of the vehicle is required.

HYBRID INERTIAL NAVIGATION SYSTEMS

The hybrid inertial naviagtion system is a combination of inertial navigation system and some other type of navigation system for the purpose of updating or improving the accuracy of the inertial navigation system. In other words, the purpose of the hybrid inertial system is to combine two navigation systems in such a manner as to retain the good characteristics of both.

There are two types of updating processes used in hybrid inertial navigation systems. One type is the damping effect which compares the inertial ground velocities with the ground velocities of some other system. The error, or difference between the two velocities are used to damp out platform errors. The other type is the reset method. This method ignores the orientation of the platform and merely resets the position of the velocity shafts periodically.

Radio Inertial

The radio inertial system is a navigation system employing an inertial navigation system

which is updated or damped periodically by a positioning system such as LORAN.

Radio and inertial navigation systems have complementary characteristics that can be integrated to provide performance characteristics and capabilities beyond the performance of either system. The inertial navigation system is used to carry the radio system through areas of poor radio reception, and the long term errors of the inertial navigation system are taken out by the radio system in areas where radio reception is good.

In a typical radio inertial navigation system, the use of LORAN is to damp the inertial velocities and update the present position. The LORAN signals used are differentiated position changes of the hyperbolic time-difference measurements. When the LORAN position changes are resolved into velocities, they can be compared with the inertial velocities and used for damping.

Doppler Inertial

The Doppler inertial is a navigation system employing an inertial navigation system which is damped by the ground velocity signals developed by a Doppler radar system. In this type of system, the use of accurate groundspeed information from a Doppler radar system is used to damp the inertially derived ground velocities.

The Doppler radar navigation system determines groundspeed by computing the apparent frequency shift of reflected electromagnetic radiation. Depending upon the velocity of the vehicle and the type of terrain, the accuracy may be in the order of a couple of feet per second. The advantage of this source of velocity is the fact that the error is not accumulative and, therefore, it can be used to null those errors in the inertial system which are accumulative. The velocities obtained from the Doppler radar are referenced to the vehicle axes. These velocities are usually designated heading and drift. In order to develop north-south and east-west velocity correction terms, the Doppler terms are resolved by the true heading angle of the vehicle. These velocities are compared with the inertial velocities, and the difference is used to damp the Schuler oscillations of the system.

Stellar Inertial

Stellar Inertial is a navigation system employing an inertial navigation system and an optical star tracker system used to eliminate the effects of gyro drift on the inertial platform. In this system, stellar observations are used to update any present position error in the inertial system. The requirements for accurate star information are as follows:

1. An up-to-date star catalogue.
2. A reliable time standard.
3. A well alined astrotracker which can be stabilized from vehicle motion.

The first two requirements are relatively easy to obtain, and the third is the limiting factor on the accuracy. Each arc second of telescope misalinement will cause 100 feet of position error; hence, for half mile accuracy, the alinement must be below 30 seconds of arc. In practice the astrotracker is directed by signals from the inertial system to a particular elevation angle and relative bearing of a reference star. Next, a search pattern is conducted until the astrotracker locates the particular body. After location, the difference in directed and actual elevation and relative bearing is computed; this, in turn, is used to update present position.

Figure 11-31 shows a simplified block diagram of a Doppler inertial system and a stellar inertial system.

Note that in the Doppler inertial system the output of the Doppler radar is a velocity function which is supplied to the second integrator of the inertial system, thus producing a distance traveled when integrated. The steller inertial system receives position information from the astrotracker which is supplied directly to the position indicator.

FUNDAMENTALS SYMMARY

The combination of accelerometers and gyros mounted on a stable element, which is continuously held level with respect to the earth and continuously holds alinement in azimuth to a true north orientation (or a known position with respect to the true north) regardless of aircraft attitude, provides the basic fundamentals from which the inertial navigation system derives all navigation computations. The computer receives accelerometer outputs, and velocity is computed by integration. Velocity is then integrated to compute distance.

AN/ASN-42 INERTIAL NAVIGATION SYSTEM

The AN/ASN-42 inertial navigation system is a hybrid inertial system which utilizes

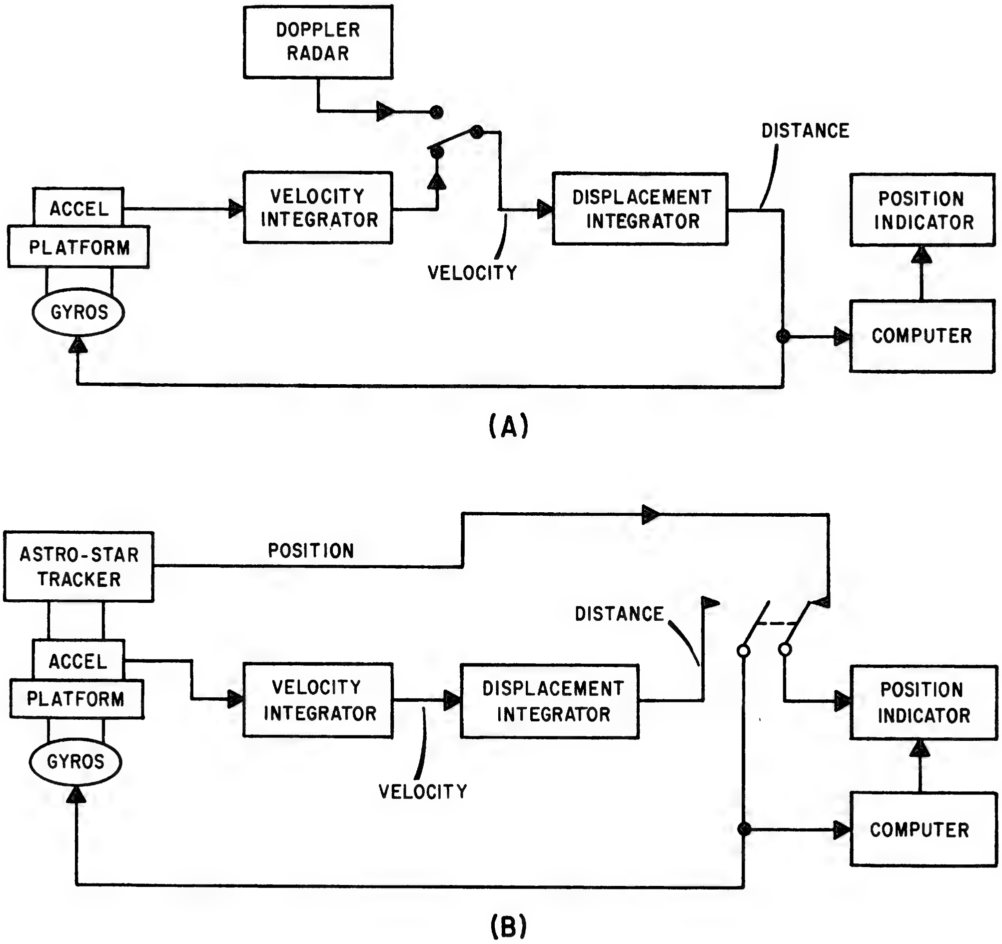

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Figure 11-31.—Simplified diagrams of hybrid inertial systems. (A) Doppler inertial; (B) stellar inertial.

outputs from the Doppler radar to damp the Schuler oscillations of the inertial navigation system. This inertial navigation system is an eight-unit, airborne, electronic inertial navigation computer. The set can operate independently of any outside information sources, but the preferred mode of operation for this system is inertial-Doppler. A description of the AN/ASN-42 components is given in AE 3 & 2, NavPers 10348-C, chapter 18. This inertial navigation system is presently installed in P-3A and B aircraft.

FEATURES OF THE AN/ASN-42 INERTIAL NAVIGATION SYSTEM

The AN/ASN-42 inertial navigation system is a highly accurate and a very versatile navigation system. This system not only provides aircraft position, (latitude and longitude) and aircraft heading relative to true north, but it also provides (depending upon the mode of operation selected) ground velocity, distance traveled, and aircraft attitude (pitch and roll) reference. For navigation near the poles, it has

an additional capability of providing grid heading for use in grid navigation.

The electrical outputs are used by the autopilot, the navigation computer, bearing-distance-heading indicators, the attitude indicator, the maneuver monitor, the radar, the TACAN, compass repeater indicators, ASW displays, horizontal situation indicators, the intervalometer, and the pilot's and navigator's plotters.

Modes of Operation

The AN/ASN-42 has six modes of operation, four of which are purely navigational modes. The other two are platform alignment modes; they are CAGE and FAST ERECT.

The cage mode is a momentary selected mode which is used to cage the platform gimbals to the airframe for a time duration of about 60 seconds, after which the system automatically goes into FINE ALIGN.

The fast erect mode is used to align the platform before operating the system in either slave or free mode. The fast erect mode enables the platform to be aligned in less than 3 minutes.

The four navigational modes of operation are as follows:

1. Inertial-Doppler.
2. Slave.
3. Free.
4. Compass.

INERTIAL—DOPPLER MODE.—The inertial-Doppler navigation mode, which is the preferred operating mode of the system, provides aircraft position in latitude and longitude, true heading, ground velocity, stabilized magnetic heading, magnetic variation, distance traveled, aircraft turn rate, and aircraft attitude in pitch and roll.

There are three submodes in the inertial-Doppler navigation mode, which are set on the alignment controller at the navigators station. They are GROUND ALIGN, OPERATE, and IN-FLIGHT ALIGN.

The ground align submode is divided into two phases, coarse align and fine align. During coarse align, the platform gimbals are caged to the airframe, and the gyro spin motors are brought up to speed. The platform is aligned in azimuth by comparing the sum of magnetic variation and platform heading with the unstabilized magnetic heading. The error signal is then brought to zero.

After 1 minute, the gyros come up to speed and the system automatically goes into fine align. In this phase, the gyros control the platform. Any acceleration signals due to components of gravity resulting from the platform not being perfectly level are amplified and filtered in the computer and applied to the level axis gyro torquers to level the platform. If the platform is misaligned in azimuth, the corrections being applied from the computer will tip it. The misalignment is thus detected by the accelerometers which then send a signal back to the azimuth gyro torquers to align platform to true north. The Doppler tie-in (signal data converter) will provide smoothed magnetic heading, computed magnetic variation, and repeated platform true heading.

In the operate submode, which is the normal system operating mode, the platform-furnished acceleration signals are summed with Coriolis and centrifugal acceleration corrections, leaving only actual north-south and east-west ground accelerations. Doppler damping is obtained by summing signals proportional to the difference between inertial and Doppler velocities with the above accelerations. The resultant signals are then integrated to obtain ground velocity. Signals proportional to velocity are summed with earth rate terms and applied to the platform to maintain its orientation with respect to the local vertical and true north.

Second integrations are performed to obtain north-south miles, east-west miles, and latitude and longitude. The latitude and longitude are displayed by the position indicator while velocities and distance traveled from the departure point are provided as electrical outputs. All the navigation, attitude, and heading outputs are provided.

The system can be made to operate in a pure inertial mode with no Doppler damping by switching the Doppler radar to STANDBY or OFF.

The in-flight submode is basically the same as ground align. However, since the system is in motion, initial velocity and acceleration information is required. Normally, it is derived from Doppler velocity information; but if the Doppler radar is inoperative, the Doppler air mass computer supplies the velocity information. The signal data computer differentiates the Doppler velocities to obtain the necessary acceleration signals, then feeds them to the velocity integrators.

SLAVE MODE.—In the slave navigation mode of operation, the system is slaved to the magnetic heading. In this mode, magnetic variation

is set in manually. The slave mode provides stabilized magnetic heading, true heading, turn rate, and aircraft attitude (pitch and roll) information. To obtain accurate true heading, accurate magnetic variation must be set in the align control. The platform is slaved in azimuth to the magnetic heading plus the manually set-in magnetic variation. This is a pendulous gyro mode which means that acceleration forces create a false gravity to which the platform attempts to level. The level error signals, therefore, actually tend to tip the platform. The resulting level error signals are torque-rate limited to slow the platform response. Thus it remains very nearly level.

When there is a discrepancy between differentiated Doppler velocity and inertial acceleration, it is considered the result of a tipped platform which causes components of gravity to be picked up by the accelerometers. This information is then used to torque the platform level. In the event that there is no vehicle acceleration, correction signal due to lack of Doppler or air mass information, a cut out signal will be used to remove the leveling signal. The platform then remains level due to the gyro forces alone.

FREE MODE.—In the free navigational mode of operation, the system maintains a fixed platform heading not necessarily related to true or magnetic north. The platform is corrected only for earth rate on the azimuth axis. The free mode provides grid heading, aircraft attitude in pitch and roll, and turn rate. In this mode, accelerometer signals are used to keep the platform level. The earth rate is computed from the latitude set on the inertial navigation controller. No correction is made for motion with respect to the earth. A turn rate cutout signal is used to remove platform leveling signals resulting from aircraft accelerations.

The platform essentially establishes its own rectangular grid coordinate system, independent of latitude and longitude. This mode is to be used in the polar regions beyond about 70° latitude, where the converging lines of longitude make normal system operation practically impossible. As in all other modes, attitude information is provided directly from the platform.

During the free mode of operation, the stabilized magnetic heading shaft and the true heading shaft located in the signal data converter may be preset to any desired heading by actuation of the SLEW switch on the copilot's inertial navigation controller.

COMPASS MODE.—In the compass navigational mode, the set provides only unstabilized magnetic heading. This is a backup mode to be used in the event of system failure or No-Go indication due to a power interruption, etc.

FUNCTIONAL DESCRIPTION OF COMPONENTS

The inertial-Doppler navigation system is fundamentally comprised of the inertial subsystem, the Doppler subsystem, and associated units. The components in the inertial subsystem are the inertial platform, the electronic control amplifier, the navigation computer, the signal data converter, the power supply, the position indicator, the alignment controller, and the inertial navigator controller. Figure 11-32 shows a block diagram of the AN/ASN-42 inertial navigation subsystem.

Inertial Platform

The main unit of the inertial subsystem is the platform assembly which contains a stabilized inertial platform or stable element, the basic attitude reference for the system. The chief function of the platform is to provide a means of accurately locating the gyros and accelerometers and to maintain their orientation fixed to the local vertical and to true north regardless of any aircraft motion.

The function and the construction of the AN/ASN-42 stable element are essentially the same as the stable element discussed earlier in this chapter, except that the AN/ASN-42 stable element does not use a Z accelerometer, which means that vertical velocity is not derived by inertial methods.

Electronic Control Amplifier

The electronic control amplifier contains the electronic amplifiers and special excitation sources required for alignment and operation of the inertial platform. These are comprised of the four gimbal servo amplifiers, two accelerometer restoring amplifiers, an azimuth caging amplifier, a 15-volt, 5-kHz excitation source, a gyro temperature control amplifier, the gyro spin motor power supply, two time delay circuits for the alignment sequence, a pitch angle detector, an azimuth demodulator and the Go, No-Go circuits.

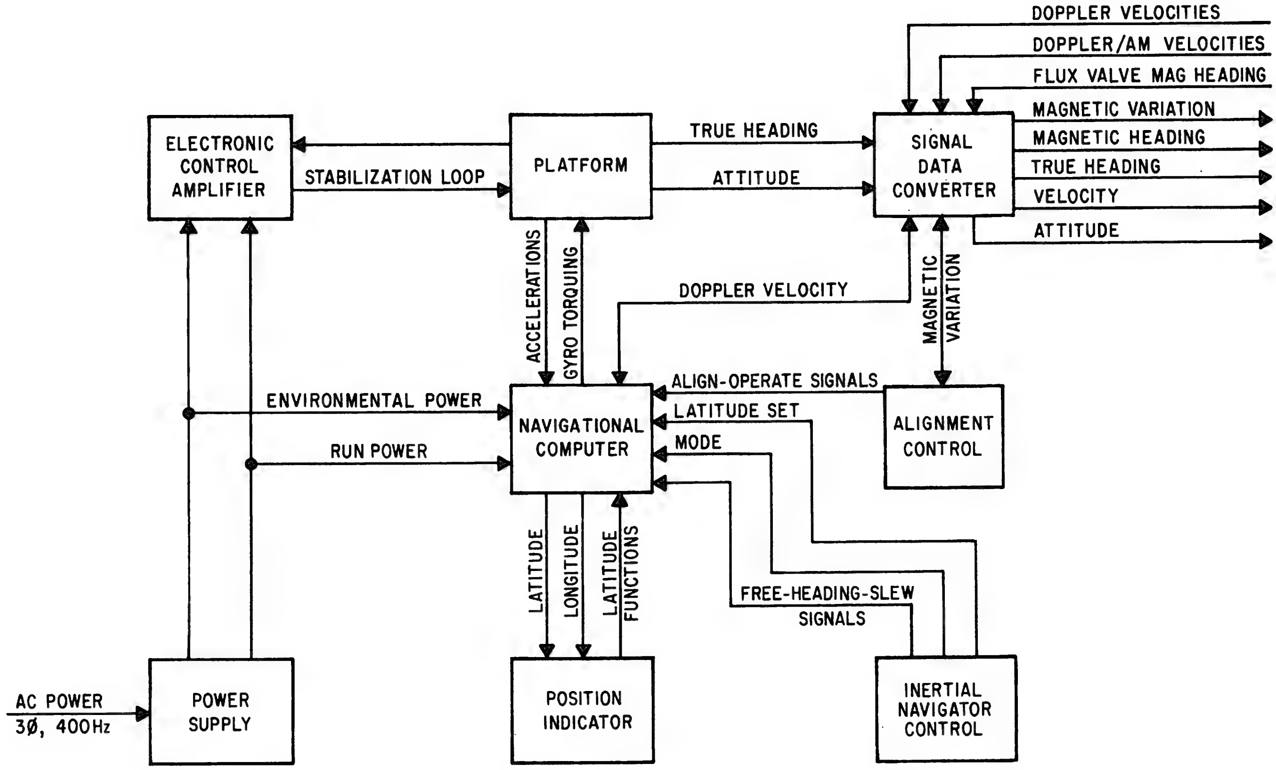

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Figure 11-32.—AN/ASN-42 inertial navigation subsystem block diagram.

Navigation Computer

The computer contains the circuitry required to erect the stable element and keep it level with respect to local gravity and oriented in azimuth to true north. This is achieved by applying torquing currents to torque coils in the horizontal and vertical axes of the gyros, causing them to precess within their individual gimbals and form a reference to local gravity rather than to inertial space. The gyro torquing currents are developed in the computer from calculations based on the measured accelerations of the vehicle along the two horizontal axes as it maneuvers over the curved surface of the rotating earth. To compute the earth rate and to maintain alignment of the gyros to true north, trigonometric functions of the changing latitude and longitude are developed in the position indicator assembly, which operates in conjunction with the computer. Integration of the horizontal accelerations to find velocities and integration of velocities to get displacement take place in the computer. The velocity and distance components resulting from integration are modified as required by trigonometric functions of latitude and longitude to produce the torquing currents applied to the gyros.

Signal Data Converter

The signal data converter provides the interconnection between the inertial and Doppler subsystems. It also contains the control circuits required to produce output information to the external aircraft equipment. Any error resulting from a comparison of Doppler with inertially determined velocity is sent to the computer, where an accelerometer compensating signal or gyro torquing signal is developed to correct the attitude of the platform gimbals. Also, in certain system modes, inertial true heading and magnetic flux valve information are compared to produce magnetic variation which is then displayed on the alignment control panel.

The signal data converter also contains an auxiliary power supply to permit operation of the magnetic heading loops when the inertial system is inoperative.

Power Supply

The power supply contains the transformers, rectifiers, and filter circuits required to provide the four primary d-c and three a-c voltages to the different assemblies of the inertial subsystem. The d-c voltages are -45, +20, +28, and +45 volts. The three a-c voltages are 12.6, 26, and 140 volts, all with a frequency of 400 Hz. Primary power 115-volt, 400-Hz, 3-phase is obtained from the aircraft electrical system. Relay actuated protective circuits and voltage sensing indicator are provided. The protective circuits automatically remove operation voltages from the inertial subsystem if any of the four primary d-c voltages fail.

Position Indicator

The position indicator contains the controls, indicators, and circuits required to display computed or present longitude and latitude. During the alignment phases, the LATITUDE SET and LONGITUDE SET switches enable the operator to preset latitude and longitude information on the digital indicators. During system operation, changes in latitude and longitude are computed by the navigational computer and the latitude and longitude counters are changed accordingly. Computed aircraft velocity information is integrated in the navigational computer to develop the latitude and longitude integrated in the navigational computer to develop the latitude and longitude integrator drive voltages are applied to latitude and longitude integrator drive motors, respectively, in the position indicator. These motors cause the LAT and LONG counters to rotate at a speed and direction proportional to the magnitude and direction of aircraft velocity. The rotation of the latitude drive motor repositions the pick-off arms of precision potentiometers whose outputs represent trigonometric functions of latitude. These outputs are used in computing aircraft velocities relative to the earth and in maintaining the stable element level with respect to the local vertical and aligned to true north.

Alignment Control

The alignment control contains the magnetic variation shaft and the switches and indicators to align the navigational computer. The mode switch permits selection of the two align modes, GROUND ALIGN and IN-FLIGHT ALIGN. Indicators on the alignment control front panel display alignment mode timing sequence and operational readiness. The alignment control also contains the controls to permit the navigator to insert local magnetic variation before ground alignment or during operation in the pendulous modes. During operation in the inertial-Doppler operate and alignment modes, local magnetic variation is computed and displayed on the MAG VAR counter located on the front panel. Magnetic variation must be manually set periodically during operation in all other modes.

The ready meter indicates the state of alignment. Two minutes before the system has completed gyrocompassing, the meter light illuminates. When the system is aligned—that is, the stable element is level and oriented to true north—the ready meter pointer enters the green GO area on the face.

The three-position alignment switch enables the navigator to energize the various alignment circuits and to initiate system operation. An interlock feature disables this switch once it has been moved from the GROUND ALIGN or IN-FLT ALIGN position to the OPERATE position. If the navigator wishes to realign the platform after the occurrence of a No-Go condition, he will switch from OPERATE to the proper align position and request that the copilot momentarily switch the inertial navigator controller to the GAGE position and then back to the I-D position. This interlock prevents the navigator from affecting the system operation without the consent of the copilot.

There are two failure lights and two indicator lights on the front panel. The COMPUTER FAILURE light will be illuminated when the ±10 volt precision reference voltage fails. The PLATFORM FAILURE light will be illuminated when the system is in the I-D GROUND ALIGN, I-D IN-FLT ALIGN, or FAST ERECT mode. The PILOT INDICATOR provides a visual indication to the navigator when the inertial navigator controller is in one of the pilot-controlled modes.

Inertial Navigator Controller

Inertial Navigator Controller (IN control) contains all the controls and indicators required by the copilot to maintain full control of the system. The six-position selector switch controls the mode of the system. It is divided into two sections, NAV (CAGE and I-D) and PILOT (FAST ERECT, SLAVE, FREE, and COMPASS). In NAV modes, a navigator is required to control the alignment controller and the position indicator. The platform is aligned to true north by gyrocompassing and the position indicator is therefore able to maintain correct latitude and longitude outputs.

In PILOT modes, the copilot controls the complete system. No navigator is required. The platform is not aligned to true north. The position indicator longitude display becomes inoperative, and the latitude counter display becomes inoperative, and the latitude counter follows the hand-set latitude from the inertial navigator controller.

SUMMARY

The AN/ASN-42 inertial Doppler navigation system is a versatile and accurate navigational aid. Operationally, it has five primary modes as well as the various submodes. In its broad functional scope, it provides attitude reference velocity, latitude and longitude, distance traveled, magnetic heading, true heading, magnetic variation, and bank angle information for the aircraft. The system is designed so that it may be operated either by the copilot alone or by the navigator and the copilot, depending upon the requirements of the particular flight.

CHAPTER 12

D-C SYSTEM CONTROL, PROTECTIVE DEVICES, AND AIRCRAFT ENGINES

Because of the increasing complexity of naval aircraft, it is essential that electrical and electronic control, protective, and warning devices be designed with a higher degree of reliability than existed in the past. In obtaining the degree of reliability required of control and protective devices, once simply constructed devices have evolved into mechanisms that are sometimes more complex than the circuits and systems they control or protect.

The description, principles of operation, and application of some of the controlling, protective, and warning devices and systems that are found in naval aircraft are discussed in this chapter.

A control device may be defined as a device, or group of devices, which serves to govern in some predetermined manner the electrical power delivered to an apparatus to which it is connected. Control relays and switches are examples of control devices.

A protective device may be defined as a device for keeping undesirable currents, voltages, or power out of a given electrical circuit. Its primary function is to protect service from interruption or to prevent or limit damage to apparatus. Protective relays, circuit breakers, fuses, and current limiters are examples of protective devices.

To classify a device as either control or protective is determined by its use in the circuit. The same relay may be used for two different purposes in the same circuit. For example, a relay is used in the auxiliary power circuit of a multiengine aircraft as a power relay (control device) to start the auxiliary powerplant; after the auxiliary powerplant has been started, the same relay is used as a reverse current relay (protective device).

RELAYS

DESIGNATION AND CLASSIFICATION

The most frequently used control and protective device is the relay. All relays have a particular classification. Their classification may be identified by the letters and numbers printed on the relay case. The designation of a typical relay is as follows:

RY	1437	A	1
Component	Basic type Indicator	Class	Enclosure

These four basic breakdowns of a relay are explained in detail in the following paragraphs.

Component

The RY stands for armature relays. However, there are various other types of relays such as thermal, plunger, polarized, and so forth, that would have a different component designation. Most of the relays that the AE works with are of the RY type.

Basic Type Indicator

This indicator identifies the basic application of the relay. A specific number within the ranges specified in table 12-1, for each basic application, is assigned to each relay.

Table 12-1.—Basic type indicator.

Symbol	Basic application
1,000 to 1,999, inclusive	General purpose.
2,000 to 2,999, inclusive	Marginal.
3,000 to 3,999, inclusive	Differential.
4,000 to 4,999, inclusive	Time delay.
5,000 to 5,999, inclusive	Latch-in.
6,000 to 6,999, inclusive	Ratchet.
7,000 to 7,999, inclusive	Selector.
8,000 to 8,999, inclusive	High speed.
9,000 to 9,999, inclusive	Sensitive.
10,000 to 10,999, inclusive	Polarized.
11,000 to 11,999, inclusive	Interlock.
12,000 to 12,999, inclusive	Special purpose.

Definitions of the basic application of relays shown in table 12-1 are as follows:

1. GENERAL PURPOSE. A general purpose relay operates when the operating voltage is applied to the coil. It has no special features.
2. MARGINAL. A marginal relay responds to make or break when the coil voltage or current reaches a prescribed value.
3. DIFFERENTIAL. A differential relay is a multiple winding relay which operates when the current or voltage difference between the windings reaches a prescribed value.
4. TIME DELAY. A time delay relay is one in which a delayed action is purposely introduced.
4. LATCH-IN. A latch-in relay is designed to lock the contacts in the deenergized position until the relay is either manually or electrically reset.
6. RATCHET. A ratchet relay operates in successive cycles according to a predetermined arrangement of impulses.
7. SELECTOR. A selector relay permits the selection of one or more circuits from a number of circuits.
8. HIGH SPEED. A high speed relay operates within 5 milliseconds after being energized.
9. SENSITIVE. A sensitive relay is designed to operate at currents of 100 milliamperes or less.
10. POLARIZED. A polarized relay is responsive to the direction of the current.
11. INTERLOCK. An interlock relay has two coils with their armatures and associated contacts arranged so that if one of the armatures is actuated, it prevents the other armature from being actuated until the first armature returns to its normal position.
12. SPECIAL PURPOSE. A special purpose relay is designed for a specific purpose or application. Relays whose applications are different from those already defined come under the heading of special purpose.

Class

The class is identified by a single letter which indicates the ambient temperature range for continuous operation as shown in table 12-2.

Enclosure

The enclosure is identified by a single digit. Table 12-3 shows these symbols and the type enclosure designated by each.

Table 12-2.—Temperature class.

Symbol	Temperature range
A	-55° C to 85° C
B	-65° C to 125° C
C	-65° C to 200° C

Table 12-3.—Enclosure.

Symbol	Type of enclosure
1	Open.
2	Enclosed (but not sealed).
3	Sealed.

Additional identifying information is contained on the relay case which is as follows:

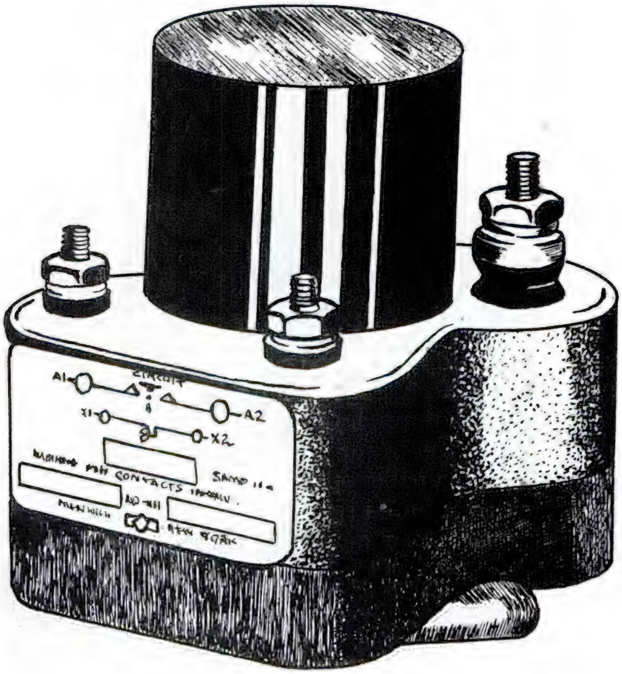
1. Rated voltage or coil current, when applicable.
2. Operating frequency, when applicable.
3. D-c coil resistance.
4. Contact rating.
5. Circuit diagram on case (applicable to sealed and enclosed relays only).
6. Manufacturer's name or symbol and manufacturer's designation.

Contactor relays (power relays) are the heavy-duty relays of the aircraft electrical system. These relays use coil currents of a fraction of an ampere up to several amperes. They are used to control power circuits carrying 600 amperes at 28 volts d.c. or 100 amperes at 120/208 volts, 3-phase, 400-hertz a.c. In addition to their high current ratings, these relays must also be capable of handling motor loads whose surge current is six times the rated load. They must also be able to open the circuit carrying ten times their rated loads for a limited number of operations.

The demands of modern aircraft have required that hermetically sealed relays be developed. A true hermetic seal is generally considered one that is metal to metal or glass to metal. Plastic or plastic rubber type gasketed seals are generally not considered true hermetic seals.

Figure 12-1 shows a typical hermetically sealed contactor relay.

Some knowledge of the basic design fundamentals of relay construction is of value for the understanding of relay operation and application.



AE.657
Figure 12-1.—A typical hermetically sealed contactor relay.

Basically, a relay is divided in three parts: the coil and its core, the contacts, and the mounting.

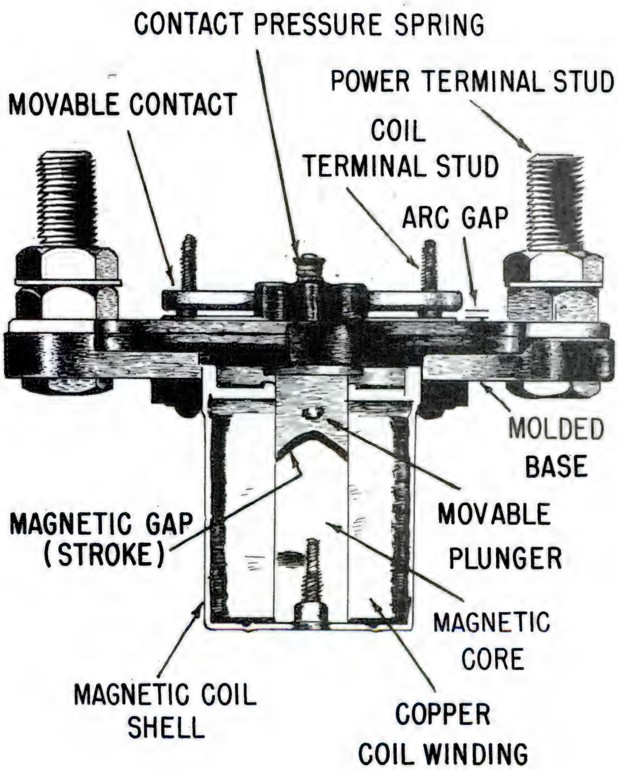
These components are used in a wide variety of forms. The configuration for aircraft control relays and power relays has been nearly standardized. A manual switch, limit switch, or other control devices energize or deenergize the magnetic coil.

When the coil is energized, the current through the coil creates a magnetic field within and around the coil which attracts the movable clapper or plunger. The contacts, which conduct the load current, are fastened mechanically to this clapper or plunger, and make contact with the nonmovable contacts to complete the circuit. Figure 12-2 shows a cutaway view of a 400-ampere, single-pole, single-throw contactor relay.

Although the contacts are a small part of the total weight, they are the heart of both control and power relays. This is especially true of the power relays. The contacts must be made of a material that does not collect a current resisting film during arcing. A high voltage such as 120 or 208 will generally break through these films, but for 28-volt d-c applications a contact material must be used which will maintain a low contact resistance and not form high resistance oxides. To test the condition of contacts or relays, measure the voltage drop across the contacts at rated load. The average voltage drop of several readings should not exceed 0.1 volt.

The size of the contacts and the material from which they are made are dictated by military specifications and by the ability of the manufacturer to meet the specifications.

Contacts may ultimately wear away if a sliding action is incorporated in the relay design. Contact material may also be lost during arcing and will ultimately result in failure of the device. The latter condition occurs primarily in d-c circuits and can be detected by the excessive pitting of one contact and the building up of a mound on its mating contact. Under these



AE.658
Figure 12-2.—Cutaway view of a 400-ampere, single-pole, single-throw contactor relay.

conditions, the life of the relay can be extended by periodic reversals of the leads to power terminals. Care should be taken to see that this is not done with polarized or polarity sensitive relays, such as reverse current relays.

Most of the power relays used in aircraft use a silver alloy contact. These contacts usually contain oxides which reduce the tendency to weld.

The contacts of smaller ampere rating contactor relays are usually secured to the contact carrier by riveting or spot welding. The larger ampere rating contactors are secured to the contact carrier by silver brazing.

Contact Support Plate

Closely allied in importance to the contact is the contact carrier or support plate.

The carrier material is selected for thermal and current carrying ability and mechanical strength. Copper, brass, and occasionally aluminum are the most common materials used. On larger power relays, the power terminal studs are usually made of brass, copper, or copper alloy because of their strength and current carrying ability.

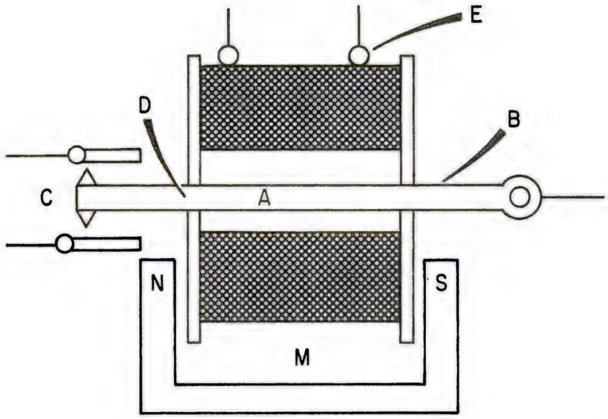
Coil and Magnetic Core

The relay coil is an electromagnet consisting of a coil and a magnetic core. The magnetic core (fig. 12-2), which consists of a magnetic material, is mounted in the coil core and fills only part of the coil core area. The plunger, which is attached to the movable contact plate, fits partially inside the coil core opposite the magnetic core. There is space between the magnetic core which allows the plunger to move toward the magnetic core when the coil is energized. The magnetic attraction resulting from the current in the coil forces the plunger to move toward the magnetic core, thus bringing the movable contacts into contact with the stationary contacts. The contacts remain closed until the current to the coil is interrupted, at which time the magnetic field collapses and the contact pressure spring opens the contacts.

TYPES OF RELAYS

Polarized Relay

A polarized relay is a relay in which the movement of the armature depends upon the direction of the current in the circuit controlling the armature. The polarity effect is usually obtained by a permanent magnet acting on the armature. Figure 12-3 illustrates a simplified polarized relay.



AE.659

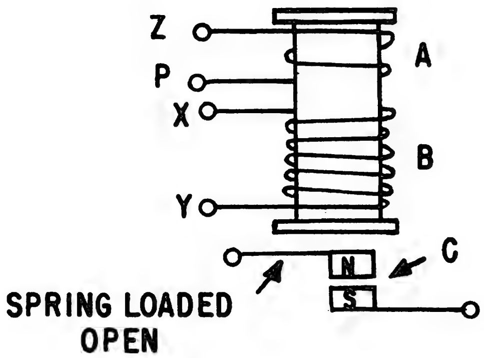
Figure 12-3.—Polarized relay (simplified).

The current which controls the pivoted armature A (fig. 12-3) goes through coil E, whose magnetic force also acts on the armature. When the direction of the current in the coil is such that it makes end D of the armature a north pole and end B a south pole, the armature is repelled by the north and south poles of the permanent magnet M, and the armature A moves upward to close the upper contacts at C. When the current in coil E is reversed, and end D becomes a south pole and end B a north pole, the armature is attracted downward to the two poles of the permanent magnet and the lower contacts at C will close. Hence, the operation of the relay depends upon the direction of the control current. Such relays are used to prevent generators from being connected to the d-c bus in reverse polarity. An example of this is the Hartman reverse current relay.

Polarized Differential Relay

The polarized differential relay employs a multiple winding (usually two). The relay operates when the current or voltage difference between the windings reaches a prescribed value. In one type of polarized differential relay, the core of the relay has two windings.

One of these windings has many turns of fine wire, while the other has a few turns of large wire. The two windings are wound on the core of the relay in opposite directions. The relay contacts are polarized: one contact is a north pole, the other a south pole. These polarized contacts are spring loaded open when the relay coils are deenergized. Figure 12-4 illustrates a simplified polarized differential relay.



AE.660

Figure 12-4.—Polarized differential relay (simplified).

The polarized differential relay is used in the Hartman reverse current relay or cutout. Its purpose is to energize the main contactor coil when the generator terminal voltage is greater than the battery terminal voltage, and, when the main contactor is closed, to deenergize the main contactor coil when current from the battery to the generator (reverse current) reaches a given value. Referring to figure 12-4, coil B closes the contacts (C) which energizes the main contactor coil and coil A opens the contacts (C) which denergizes the main contactor coil. Briefly, coil B closes the contacts (C); coil A opens the contacts (C).

The principles of operation of the polarized differential as used in the Hartman reverse current cutout is as follows: When the d-c generator voltage reaches approximately 23 positive, a polarized relay similar to the one shown in figure 12-3 connects coil B across the open main contactor such that terminal X of coil B is connected to the generator positive and terminal Y is connected to the battery positive. When the generator terminal voltage is less than the battery terminal voltage, the direction of the electron flow (current) in coil B is from X to Y, which produces a south pole in the coil core adjacent to the contacts (C). This attracts the north polarized contact of the contacts (C), which keeps the contacts open. When the generator terminal voltage is above the battery terminal voltage, the direction of current is from Y to X. This produces a north pole in the coil core of coil B adjacent to the contacts (C), which repells the north polarized contact. The contacts are set to close when the potential difference between the generator and battery reaches a predetermined value. In the Hartman reverse current relay, the contacts are adjusted to close when the generator terminal voltage is about 0.5 volt greater than the battery terminal voltage.

Closing the contacts (C) energizes the main contactor coil, which closes the main contactor, thus connecting the generator to the line through the heavy winding of coil A. Closing the main contactor shunts coil B which places terminals X and Y at the same potential, thus current in coil B drops to zero which inactivates the coil until the main contactor opens. The contacts (C) are held together by their magnetic attraction, which is greater than the spring tension trying to separate them, and they remain closed until they are opened by coil A.

To open contacts (C), the current in coil A must satisfy two conditions: (1) The current must be in a direction to produce a south magnetic pole adjacent to the contacts (C) and (2) the current must be of such magnitude so as to produce a magnetic attraction strong enough to overcome—with the aid of spring tension—the mutual magnetic attraction of the contacts.

Meeting the first condition requires that the current must be in the direction P to Z.

The second condition is variable and is a matter of design. In the Hartman reverse current relay, a current of 18 to 35 amperes is required.

Marginal Relay

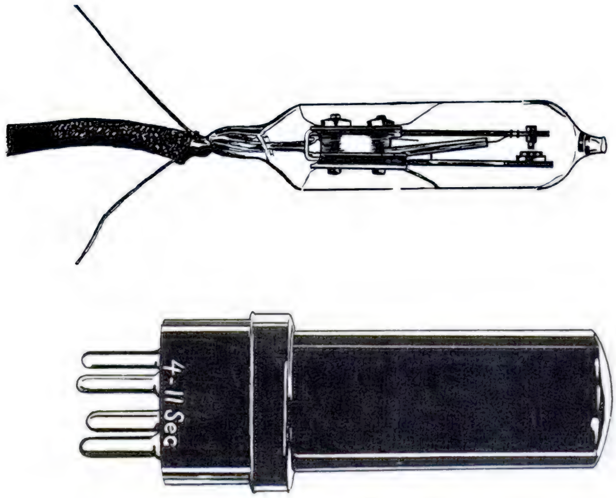
A marginal relay responds to make or break open or to close its contacts when the coil voltage or current reaches a predetermined value. Examples of marginal relays are overvoltage relays, equalizer relays, and dropout relays.

Overvoltage relays provide overvoltage protection to systems and parts when overvoltage occurs. Overvoltage may be caused by failure

of the voltage regulator or by short circuiting of the generator field to a voltage source.

The overvoltage relay is a sensitive, normally open relay. The relay coil is calibrated to trip at a safe predetermined value, usually at 30 volts, ±0.5 volt, when protecting a 27.7-volt system. The contacts of the relay are in series with a field trip relay which when energized will open the generator shunt field.

The overvoltage relay coil is in series with one and sometimes two resistors. Some overvoltages relays are equipped with a capacitor for time delay closing of the overvoltage relay to prevent transient overvoltage from tripping the generator off the line. If two resistors are used, one is fixed and the other adjustable. Adjusting the variable resistor, determines what value of overvoltage will cause the relay coil to close its armature, thus opening the generator field circuit.



AE.661
Figure 12-5.—Thermal time delay relay.

Time Delay Relay

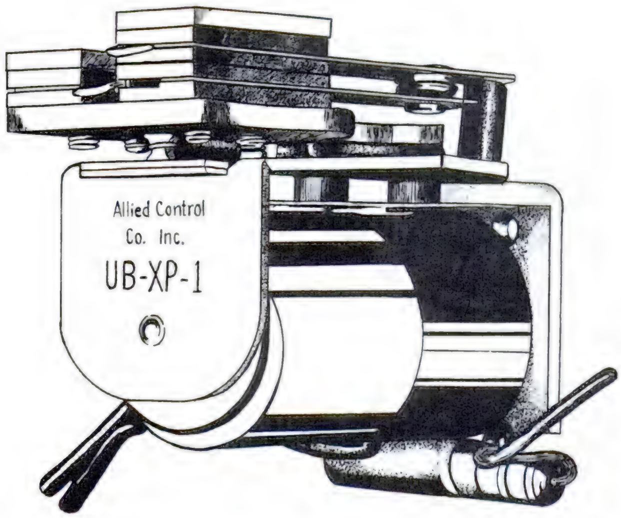
The time delay relay is a relay that has a delaying action purposely introduced. Two common types of time delay relays are the thermal time delay relay and the lag coil time delay relay; and one not so common is the dashpot time delay relay.

THERMAL TIME DELAY RELAY.—The thermal time delay relay uses a bimetallic element which bends as it is heated. The element is made by welding together two strips of different metals having different thermal expansion rates. A heater is mounted on the element itself. As the heat causes the element to bend, because of the different thermal expansion rates, these contacts close to operate a relay. The delay time of the bimetallic strips is usually from 1/2 to 1 1/2 minutes and is varied by using metals with different expansion rates or by increasing or decreasing the distance between the fixed and moving contacts. Figure 12-5 illustrates a thermal time delay relay.

LAG COIL TIME DELAY RELAY.—The lag coil time delay relay utilizes a lag coil which is sometimes referred to as a slug. This is usually a large copper slug that is located at one end of the coil winding or a tubular sleeve that is located between the winding and the core.

The lag coil acts as a shorted secondary for the relay coil. The changing flux in the relay coil (when it is energized or deenergized) induces a current in the lag coil (slug) that creates a counter magnetomotive force which causes a delay in the closing and opening of the relay. Figure 12-6 illustrates a lag coil time delay relay.

DASHPOT TIME DELAY RELAY.—The dashpot time delay relay is used in some time delay applications. A magnetic coil pulls a plunger through a dashpot which may be either oil filled or air filled. A small hole in the plunger allows the oil or air to pass through. The time delay



AE.662
Figure 12-6.—Lag coil time delay relay.

can be varied by changing the size of the hole in the plunger.

Latch-In-Relay

The latch-in-relay is designed to lock the contacts in the deenergized position until the relay is either manually or electrically reset. A good example of the latch-in relay is the field relay employed with the overvoltage control circuit that is used in many multigenerator aircraft. In this particular circuit, the field relay opens the generator field circuit when the field relay has been energized by the overvoltage relay.

The latch type field relay has two windings. One is the trip coil, and the other the reset coil.

Energizing the trip coil opens the movable contacts, which are mounted on a spring loaded armature. After the contacts open they are held in the open position by a mechanical latch. The mechanical latch is unlatched when the reset coil is energized, thus allowing the contacts to close again. Figure 12-7 illustrates an electrically reset latching relay.

CONTACTOR AND FEEDER PROTECTOR RELAY

Since aircraft generators are capable of delivering high currents, dangers resulting from shorts and grounds must be guarded against. The contactor and feeder protector relay is designed to protect against such dangers.

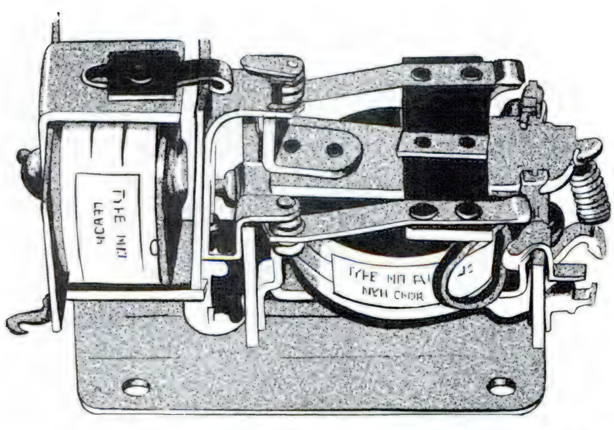


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Figure 12-7.—Electrically reset latching relay.

A contactor and feeder protector relay works in conjunction with a ground and feeder protector relay. The purpose of this relay is to connect and disconnect the generator to the d-c essential bus. It also provides feeder protection between the ground and feeder protector relay and itself.

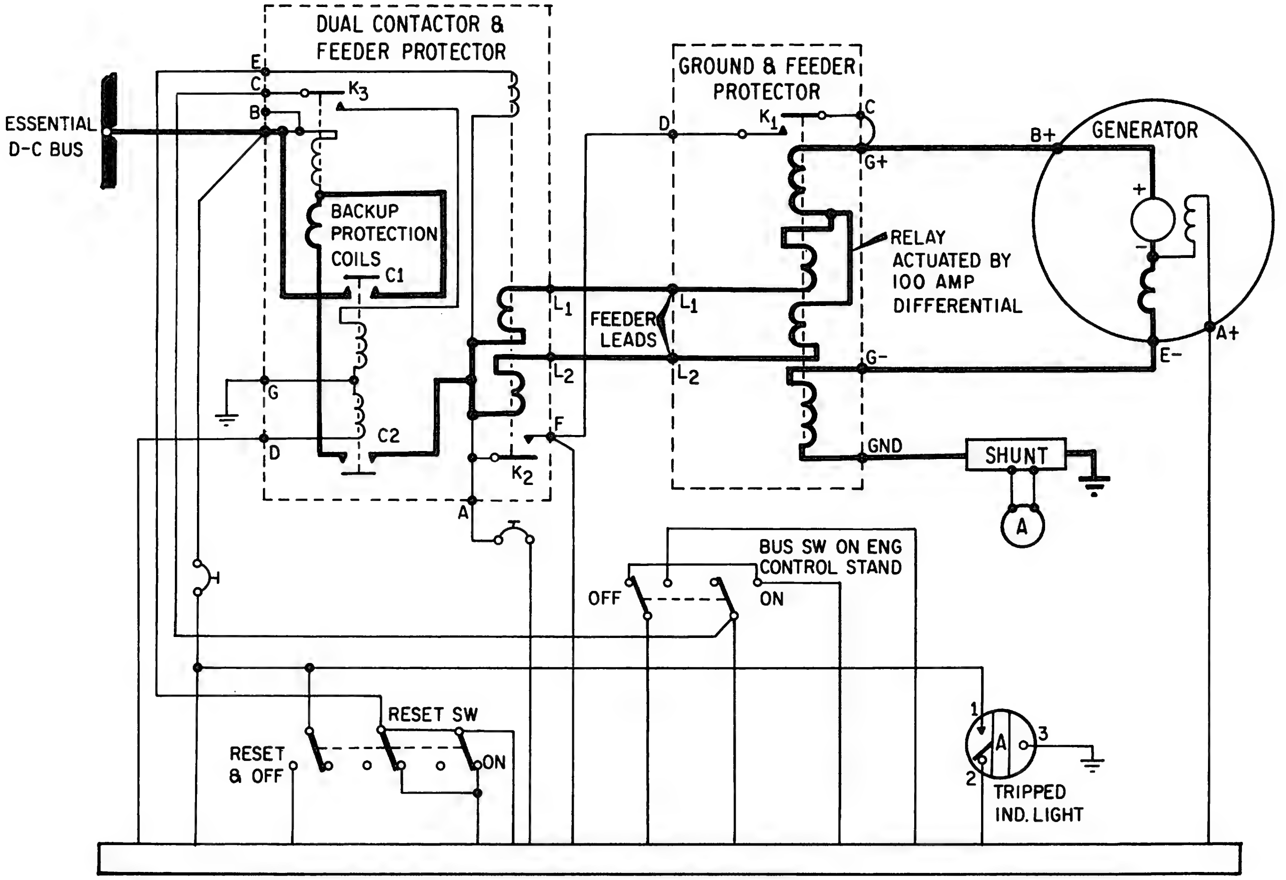
Normally, the ground and feeder protector relay is located as close to the generator as practical, and the contactor and feeder protector is located at the essential d-c bus.

The contactor and feeder protector assembly is shown in figure 12-8. The ground and feeder protector is also shown as it is connected to the generator. Both of these relay units contain a differential current relay with opposed current coils. The coils are wound so that equal and opposite flux is produced by each coil when equal currents flow in each coil.

Referring to figure 12-8, when the generator is operating normally, relay K3 in the dual contactor and feeder protector relay is closed and the generator is tied to the essential bus by contactors C1 and C2. Looking toward the generator from contactor C2, the generator current divides equally through a pair of differential current coils and is conducted by two parallel feeder leads to the ground and feeder protector. In the ground and feeder protector the generator current passes through another pair of differential current coils and then joins up again. When no fault exists in the feeder system, equal currents are carried by the feeder leads which create equal and opposing magnetic fields in each pair of differential current coils; thus, the contacts of relays K1 and K2 remain open.

A fault in either feeder lead redistributes the current in the two feeder leads resulting in a flux imbalance in one or both of the differential current coil pairs, thus causing the relay contacts of K1 or K2 to close. When either relay K1 or K2 closes, the field relay in the generator control (not shown in figure 12-8) opens (trips), which disables the generator causing it to disconnect from the line.

A second pair of windings in the ground and feeder protector unit has one winding connected in series with the generator power positive lead and one winding connected in series with the generator power ground lead. The power and ground lead coils similarly oppose each other, so that a fault in either lead or in the generator will cause the differential relay to close and trip the system.



AE.664

Figure 12-8.—Schematic diagram of the dual contactor and feeder protector relay.

The differential relay in the dual contactor and feeder protector has a third winding through which flows most of the field current and control circuit currents. This coil serves to trip the field relay and remove the generator from the line in case of faults in the field or control circuit.

In addition to the differential relay, the dual contactor and feeder protector contains dual contactor relays which have their contacts in series with the essential bus to insure positive interruption of the generator current during a reverse current condition. With two contactors in series, the failure of one contactor to open on reverse current, due to freezing of its contacts or failure of the normal reverse current relay, is backed up by the action of a second contactor. This second contactor is energized through the parallel coil of the backup protection relay, which is shorted out when the contactor closes. However, the series coil of the backup relay is in series with the main line and keeps the contactor energized. If, on reverse current, the first contactor fails to open, the series coil forces its contact open, at a set amperage, dropping out the contactor, and thereby disconnecting the generator from the bus. If a heavy surge of reverse current flows from the bus, both contactors open almost simultaneously.

D-C CONVERTERS

TRANSFORMER-RECTIFIERS

Increased electrical loads and the weight/load factor have caused the modern Navy to change from conventional d-c generator systems to the more versatile a-c systems. However, many naval aircraft still require a source of d-c

power. The transformer-rectifier is utilized within the a-c power system to satisfy this requirement.

Transformer-rectifiers are discussed in AE 3 & 2, NavPers 10348-C; therefore, no attempt is made to repeat that material here. However, the d-c converter is discussed along with the circuitry involved in this modern method of d-c supply.

Figure 12-9 shows a schematic of a d-c converter.

The input voltage is supplied directly to the transformer's 4-wire, wye-connected primary. This input voltage is stepped down by the transformer and the output voltage is taken from the transformer by two secondaries, one wye-connected and the other delta-connected. The wye-delta secondaries are used to minimize ripple and to divide the load among the various sections of the rectifier.

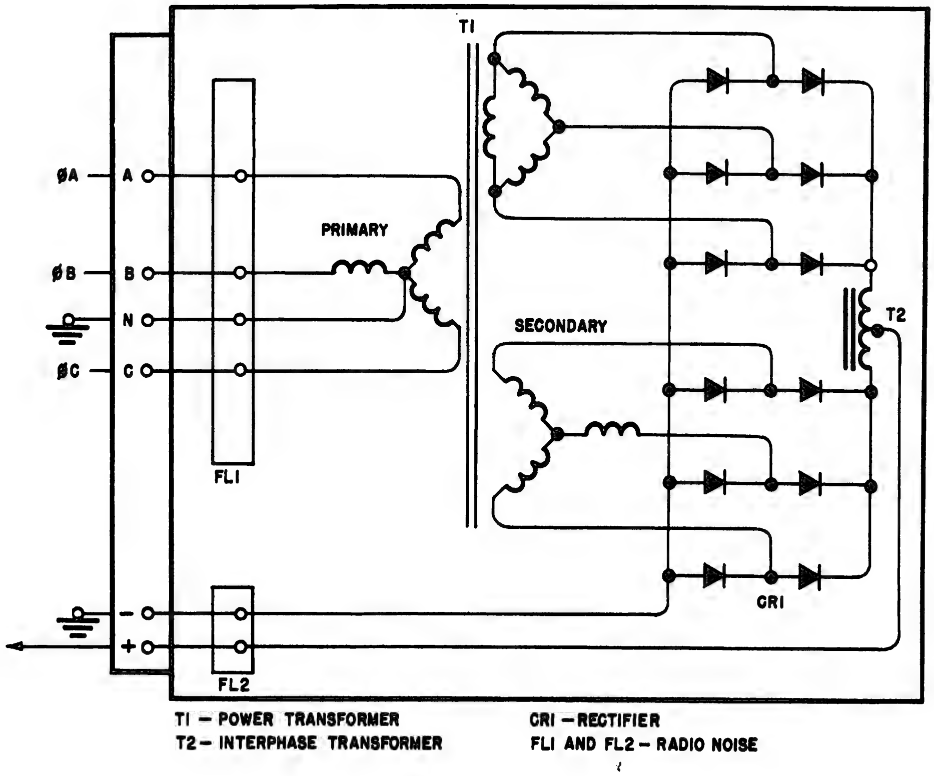
Rectification of the transformer secondary output voltage is accomplished by utilizing 12 silicon diode rectifiers which are connected to form two 3-phase full-wave bridges. The bridges are in parallel on the d-c side and each is supplied by one of the transformer's secondaries. The interphase transformer is utilized within the converter to keep the ripple voltage from exceeding 1.5 volts between 0 and 50 percent load conditions and 1.0 volt between 51 and 100 percent load conditions.

Some d-c converters contain fans for cooling while some installations depend upon the aircraft cooling system.

D-C UNDERVOLTAGE PROTECTION

Some aircraft which have an unregulated transformer-rectifier system utilize an undervoltage device for protection of the d-c electrical system. Such a system is depicted in figure 12-10. (The schematic illustrates alternate power being supplied.)

The undervoltage protection system consist of two relays; the d-c undervoltage relay and the d-c undervoltage control relay. The d-c



AE.665

Figure 12-9.—Schematic diagram of a d-c converter.

undervoltage relay is a thermal relay. It monitors the output voltage of the primary converter and becomes deenergized if the voltage output drops below approximately 23 volts. The contracts of the relay are normally open.

The d-c undervoltage control relay operates on 28-volts d.c. The pickup voltage for this relay is 18 volts with a dropout voltage of approximately 7 volts. In the event of a primary d-c converter failure, the relay deenergizes and completes the control circuit which energizes the alternate converter control circuit, thus placing the alternate converter on the line.

D-C CONVERTER FAILURE INDICATION

Should a malfunction occur to the primary d-c converter, the contacts of the undervoltage control relay will complete power to the caution light. This indication system is discussed in this chapter under the heading of "Power Warning and Indicating Lights."

POWER AND NONINSTRUMENT WARNING DEVICES

In today's combat aircraft, many different electrical, mechanical, and hydraulic systems must operate simultaneously. It is necessary to provide a visual indication of equipment trouble or alternate operation of equipment to the pilot and his crewmembers. Warning and indicator lights are used since they are small in size, light in weight, low in cost, and attract one's eyes at the instant they are energized. The brilliance of the warning and indicator lights is usually controlled by a rheostat or autotransformer. The operational condition of the light can usually be tested by a warning light test switch; in most circuits the light is a push-to-test type. These warning and indicator lights are installed in the following circuits:

1. D-c and a-c power circuits.
2. Positioning circuits.
3. Quantity and pressure circuits.
4. Overheat circuits.

POWER WARNING AND INDICATING LIGHTS

Warning and indicating lights used in power circuits give visual indication under the following conditions:

1. When the generator fails to supply voltage to the essential bus.
2. When a power circuit becomes shorted or grounded.
3. When the armament bus has voltage applied to it.
4. When an inverter fails to supply an a-c voltage of the correct amount and frequency to an a-c bus. For an example of a warning light circuit, refer to figure 12-11 which shows a warning light used in the d-c power and control circuit of a current aircraft.

This d-c power failure indicating system provides the pilot with a visual indication of the failure of the primary d-c converter. The system consists of a master caution indicator, a d-c caution light, relays, a full-wave rectifier, and associated circuitry.

When the output voltage of the primary converter drops below 23 volts, the d-c undervoltage control relay is deenergized and the d-c power failure indicating system circuit is completed, the d-c power caution light is illuminated and the master caution indicator presents an illuminated (yellow and black) flashing barber pole indication to the pilot.

Testing of the d-c power caution light is accomplished by depressing the warning light test switch, which directs the rectifier output to the caution light through the energized test relay.

The indicating system utilizes both 28-volt d-c and 120-volt a-c power. The 28-volt d-c power from the essential d-c bus is supplied to the master caution indicator and the indicating system test circuit. The 120-volt a-c power is directed to the essential autotransformer. The autotransformer provides 28 volts a-c to the full-wave rectifier.

The full-wave rectifier is utilized because the caution light is controlled by 28-volt d-c power. If the primary d-c converter fails, d-c power must be available for the caution light. This power is supplied by the autotransformer through the rectifier.

POSITION WARNING AND INDICATING LIGHTS

Lights that are used in positioning circuits are important since they indicate either a safe or unsafe condition of a particular control or mechanism. The pilot relies upon these indications in determining the safe operation of the aircraft. Some of the circuits that utilize these lights are landing gear, tailhook, hatch, and air deflectors.

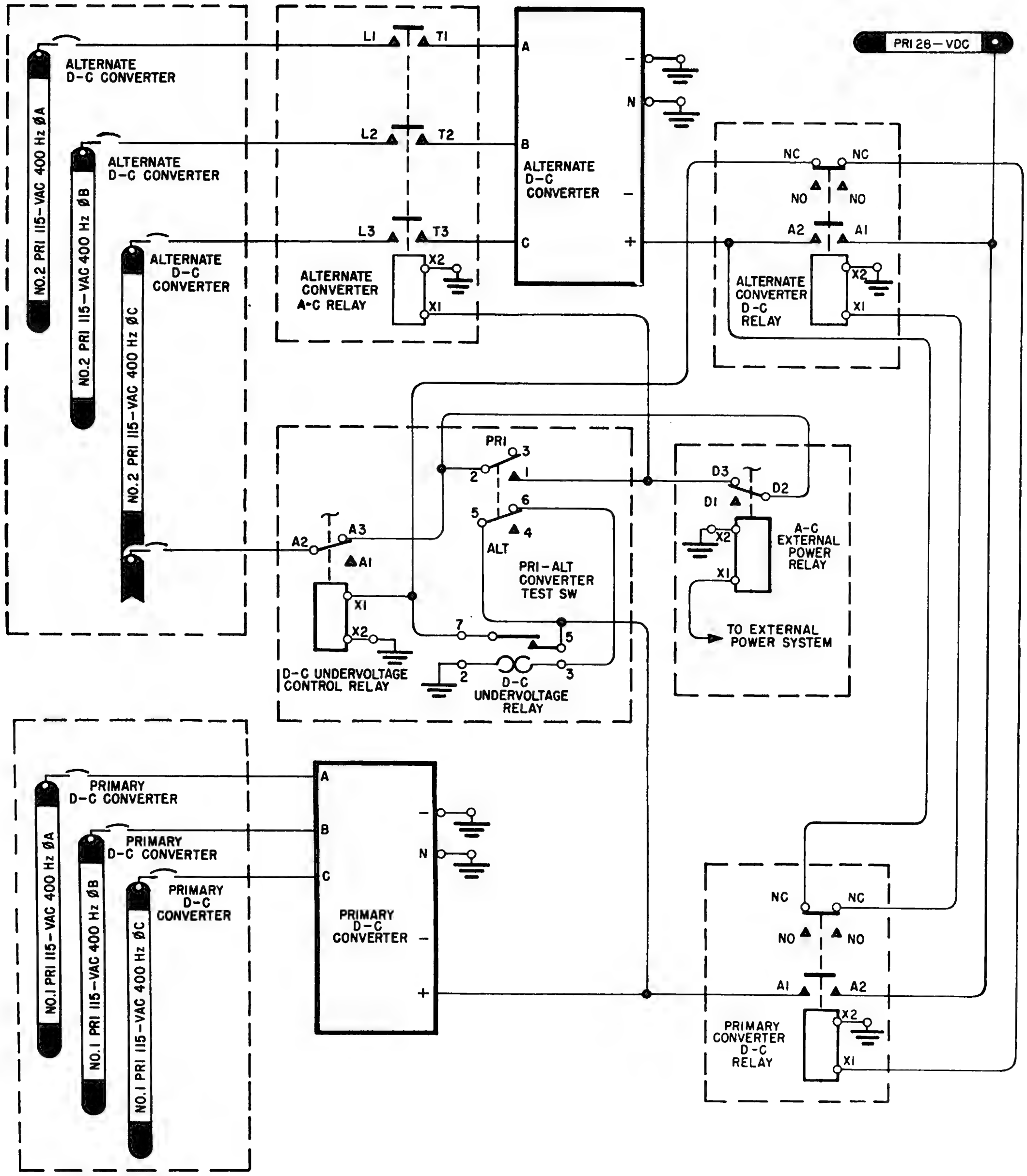


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Figure 12-10.—D-c power supply schematic.

Figure 12-12 illustrates an air deflector with an indicating light circuit.

One of the Navy's large troop/cargo aircraft has air deflectors mounted aft of each wheel well to deflect airflow from the paratroop jump door area. These air deflectors are electrically operated by a motor and reduction gear actuator.

An adjustable door warning switch on the fuselage structure operates the door warning light on the paratroop panel when the air deflectors are not fully closed.

When the control switch is placed in the closed position, the air deflector isolation relay is actuated, applying power to the retract fields of the actuators. The deflectors begin to

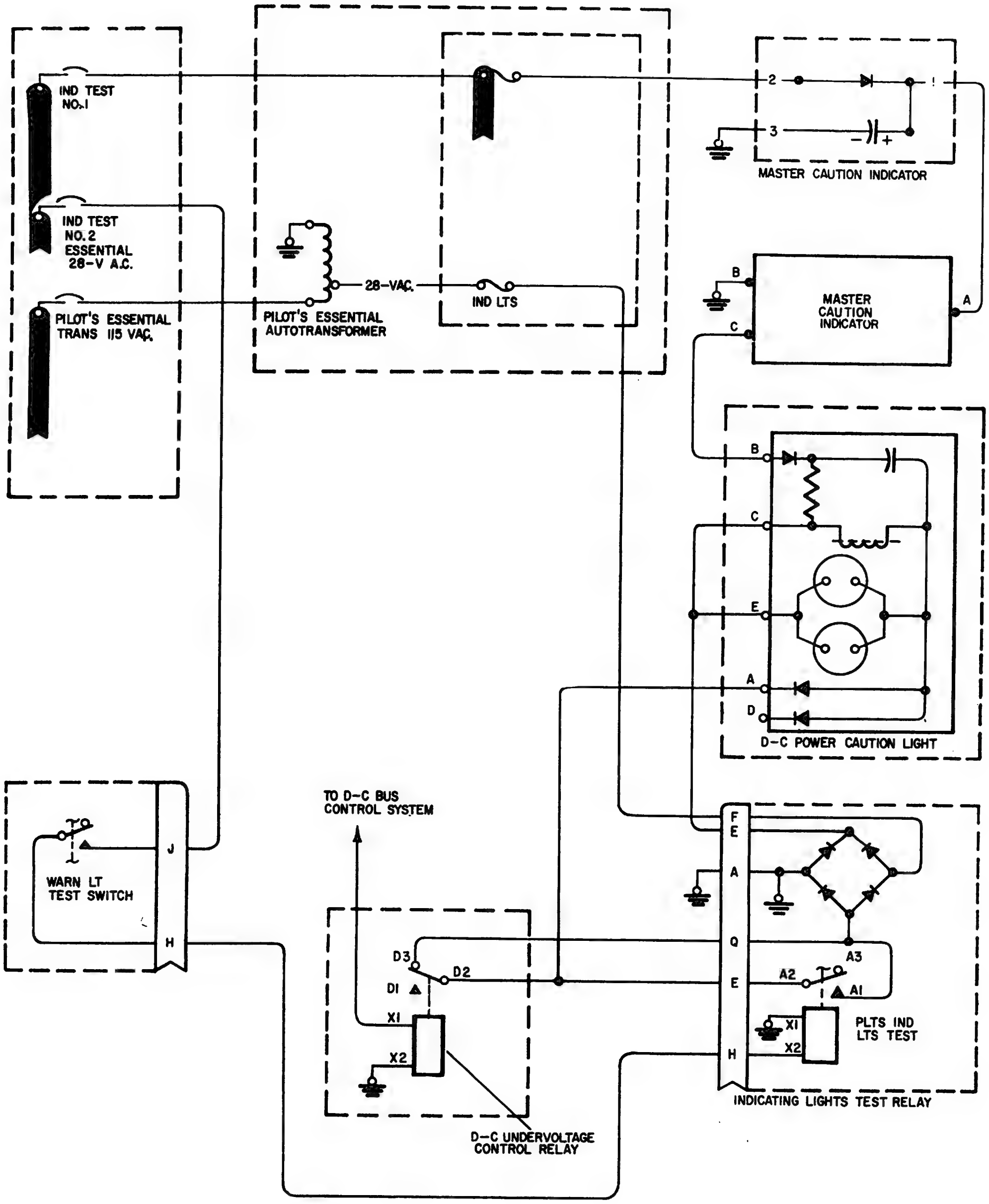

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Figure 12-11.—D-c power failure indicating system schematic.

close, but the warning lights continue to glow until the deflectors are completely closed.

OVERHEAT WARNING AND INDICATING LIGHTS

These lights are used for warning and indicating when an overheating has occurred. For example, this may occur as a result of the following:

1. A generator overheating due to the lack of ventilating air.
2. An overloaded generator.
3. A bearing becoming overheated.
4. A shorted or grounded generator field.

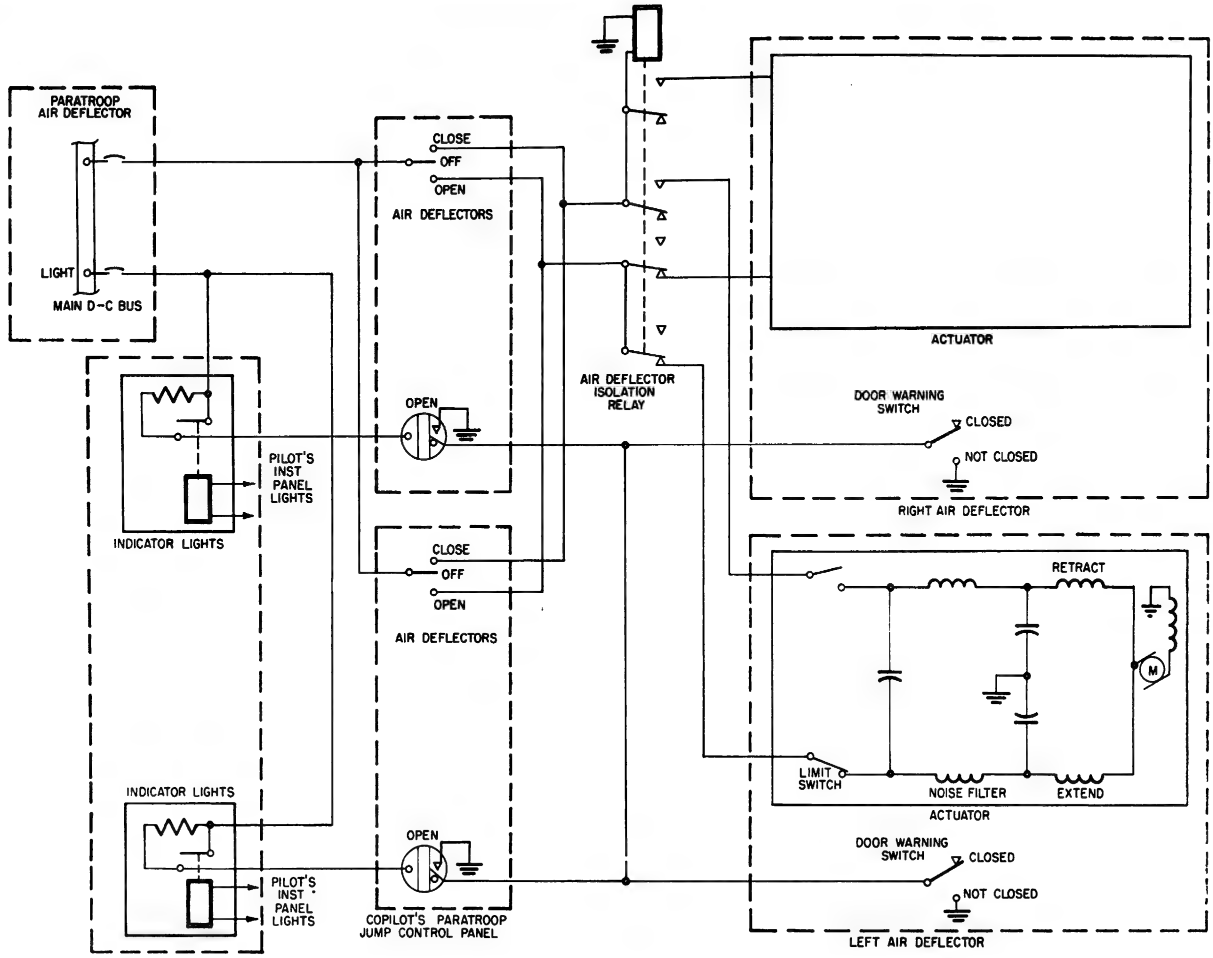

Figure 12-12.—Air deflector circuit schematic diagram.

Figure 12-13 shows a schematic of a generator and constant speed drive system overheat warning circuit. The system consists of indicator lights, a test switch, and thermal switches. The thermal switches are mounted on the generator and constant speed drive assembly. These switches are designed to close when the temperature reaches a specified temperature. As the contacts close, a ground is completed to the overheat warning lights. These lights are located where the pilot and crewmembers can easily see them, and thereby detect the trouble before serious damage occurs.

Fire detection systems have become an essential warning device in almost every naval aircraft. The system warns the pilot by illuminating a "fire warning light" located in the cockpit whenever there is a fire or an overheat condition in engine nacelles or cavities. Figure 12-14 shows a typical jet engine fire detection sensing circuit.

A schematic diagram of a fire detection system is shown in figure 12-15. A typical fire warning sensing element consists of an Inconel (nickel chromium iron alloy) tube enclosing two Inconel wires that are separately embedded in a specially formulated ceramic electrolytic substance. This ceramic substance has physical and electrical properties such that it has a high resistance at temperatures below an overheat condition temperature, has a marked decrease in resistance at temperatures approaching an overheat condition, and can withstand heat transients of 3,000° F and above.

When the temperature reaches an overheat condition, the resistance of the cermaic core decreases so that a small current flows between the wires. The control units, which are rate-sensitive, transistor operated, monitor the resistance of the sensing elements and are triggered by a drop in resistance of the sensing element.

The control unit circuit consist of a relay controlled by a bistable multivibrator and a regulated power supply. Transistors Q101 and Q102 make up the vibrator circuit which causes the relay, K101, to energize when the circuit is triggered. Transistor Q103, resistor R107, and diode CR108 are used to maintain voltage regulation, since the circuit is sensitive to any voltage variations at the sensing elements. Capacitor C101 is the circuit element which provides rate sensitivity.

When the fire detection test switch is actuated, 115-volt a-c power is routed to the test relay. Energizing the test relay shorts the inner conductors together, simulating a resistance reduction in the sensing elements. All the control units then function as if an actual fire or overheat condition existed.

ANGLE-OF-ATTACK AND STALL WARNING SYSTEMS

The angle-of-attack system is essentially a servosystem that is used primarily on carrier type aircraft to:

1. Provide a visual indication of the angle-of-attack of the aircraft.
2. Actuate cam operated electrical switches at preselected angles of attack which illuminate the approach lights and the pilot's indexer lights.
3. Actuate the rudder shaker or stick shaker circuit when the aircraft is nearing a stall attitude, thus warning the pilot of an impending stall.

Figure 12-16 is a simplified diagram of an angle-of-attack system.

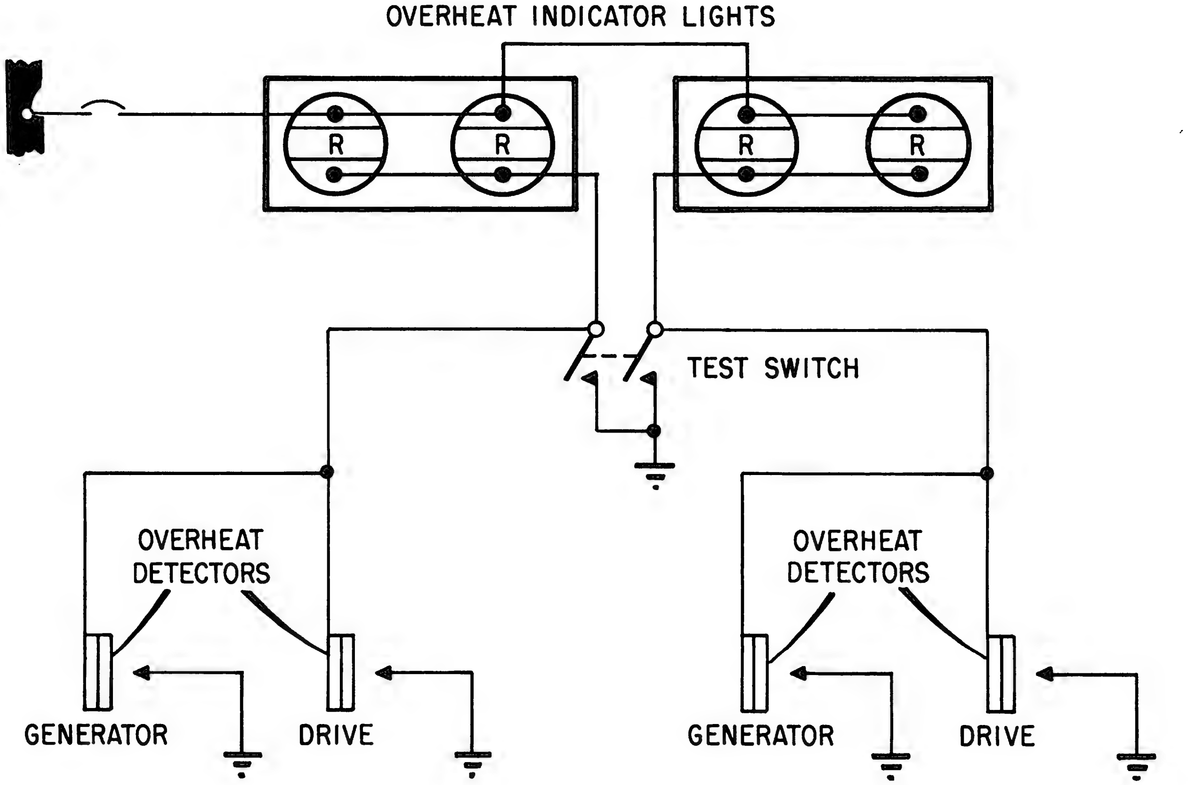

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Figure 12-13.—Generator and constant speed drive overheat schematic diagram.

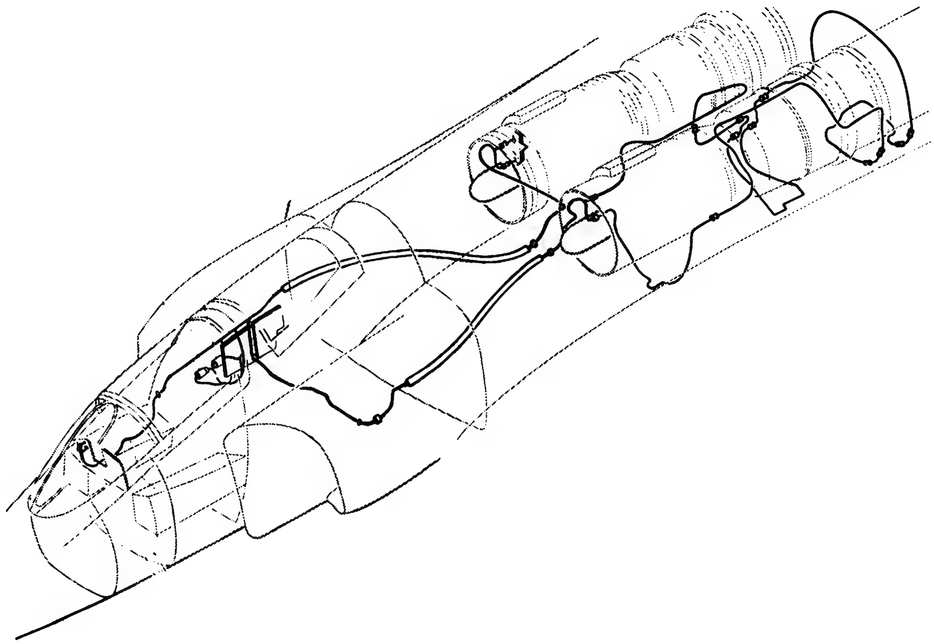

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Figure 12-14.—Jet engine fire detection sensing circuit.

AIRSTREAM DIRECTION DETECTOR

The airstream direction detector measures the direction of local airflow with an accuracy of 0.1 degree at indicated airspeeds in excess of 90 knots. The body of the unit is mounted within the fuselage and the cylindrical probe extends outward through the skin of the fuselage. Dowel pins in the circular mounting flange engage mating holes in the mounting plate, which is part of the airframe, to assure proper angular positioning.

The tubular probe is sealed at both ends and is divided into two parallel air passages by means of a full length separator. Two longitudinally parallel slots, one for each passage, are milled through the wall of the probe near its outward end and two corresponding orifices are drilled into the passages near the base of the probe. The main housing casting is cylindrical and encloses a balanced paddle which is pivoted on ball bearings.

Outside the paddle chamber a crank arm on the end of a paddle shaft engages an arm, fixed to the base of the probe, to transmit paddle rotation to the probe. The arm fixed to the probe carries two wipers incorporated with two electrically independent toroidal potentiometer windings. These potentiometers provide an electrical signal dependent on probe position. Only one of these potentiometers is used for the angle-of-attack system; the other is used as a source of angle-of-attack information for other computing equipment in the aircraft. A thermostatically controlled deicing heater is enclosed within the separator in the probe; and an additional thermostatically controlled internal heater eliminates condensation within the unit.

A cover for the probe is supplied with each airstream direction detector to protect the internal mechanism when the aircraft is parked in the open or when the aircraft is being washed down.

RELAY UNIT

Some installations employ a relay unit. In these installations, the relay unit houses the various electrical components of the servosystem and serves as a junction point for the system wiring. This relay unit contains a sensitive polarized relay, a power relay, two

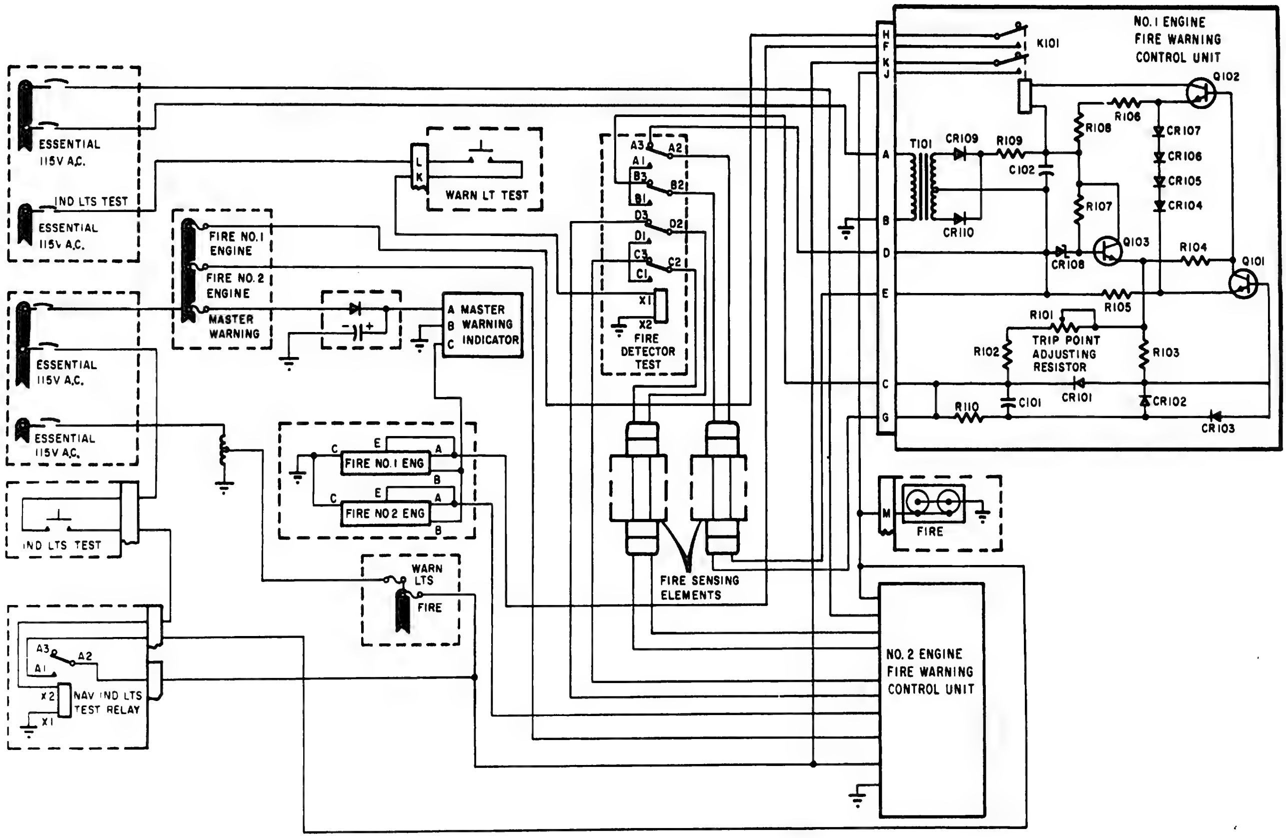

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Figure 12-15.—Fire detection schematic diagram.

approach light relays, a filter, and a manual reset thermal circuit breaker located in the probe heater circuit.

INDICATOR UNIT

The indicator unit is mounted on the instrument panel so that its dial and pointer are visible to the pilot. The dial is graduated from 0 to 30 in 15 increments. A pointer sweeps from 0 to 30 as the probe of the airstream direction detector is rotated from one limit to the other. A movable reference index can be positioned along the outer edge of the scale by rotating a knob at the lower corner of the mounting flange.

The dial light is contained in a removable housing at the upper left of the dial. The dial is adjustable one-half scale division either way from center to compensate for airframe tolerances in the zero lift angle of attack in individual aircrafts of like type. At the center of the adjustment range, the zero graduation on the dial is alined with an index mark on the bezel. The dial is clamped in position by two set-screws in the bezel. Adjustment of the angle-of-attack indicator is covered in AE 3 & 2, NavPers 10348-C.

An angle-of-attack indicator schematic is shown in figure 12-17.

The indicator consists of a sensitive relay, a separate polarized servomotor, a potentiometer, and a dial. When the input signal from the airstream direction detector and the input signal on the indicator control windings are balanced, there is no current in the relay control windings. Therefore the relay provides zero average power to the servomotor.

When the angle of attack of the aircraft changes, the input to the relay control winding B becomes negative or positive with respect to the followup potentiometer. The polarity of the

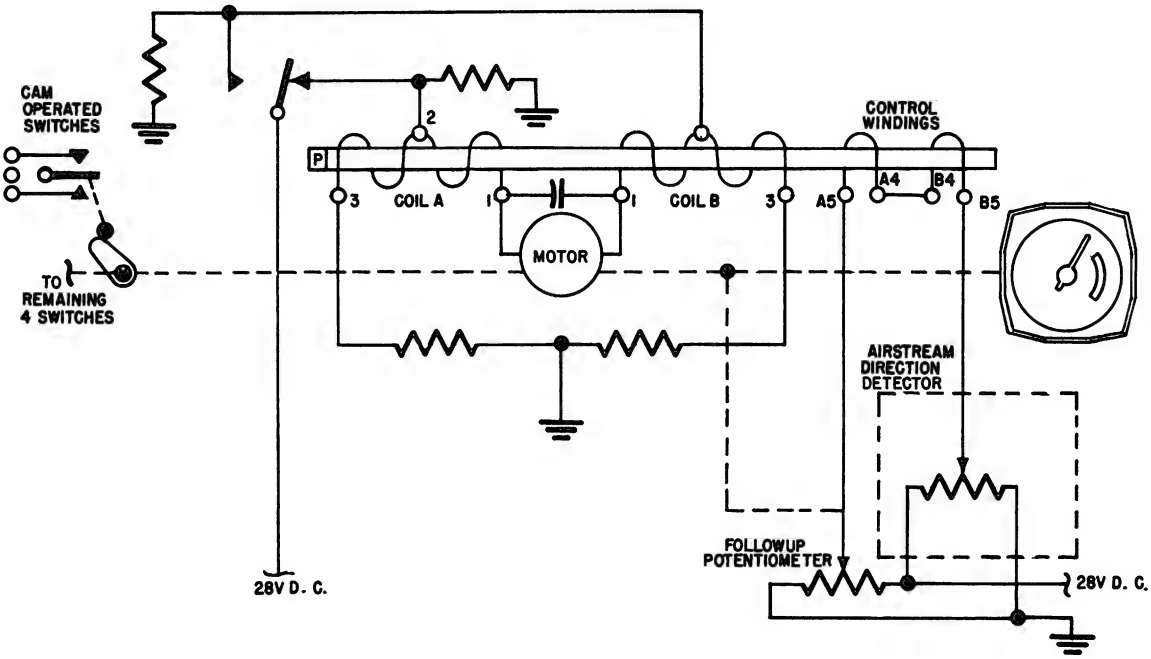

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Figure 12-16.—Simplified diagram of an angle-of-attack system.

error signal is sensed by the relay which provides power to drive the motor in the proper direction.

Since the followup potentiometer is geared to the motor, the motor rotates until the followup potentiometer setting is equal to the output of the potentiometer from the airstream direction detector.

When the motor rotates, it drives a shaft. There are five cams on the shaft which operate five switches. These switches control the approach lights, index lights, and the stall warning vibrator (if installed).

The indicator contains a flag which indicates OFF when power has been removed or lost.

VARIABLE NOZZLE SYSTEM

The variable nozzle system (fig. 12-18) is composed of electrical, hydraulic, and mechanical components which position the variable exhaust nozzle for exhaust gas temperature control and optimum thrust at all power settings. Nozzle area is changed according to engine operating conditions in order to obtain the desired thrust while maintaining safe operating conditions throughout the engine.

The nozzle area is scheduled by the nozzle area control. The control uses three signals (power lever position, nozzle position, and exhaust gas temperature (EGT)) to regulate the output of the nozzle pump. The power lever position, transmitted to the nozzle area control by the power lever linkage flexible cable, schedules the nozzle almost full open, up to and at idle rpm. When the power lever is advanced from idle, the nozzle closes to a smaller area (often referred to as the cruise area) following a mechanical schedule. As the power lever is advanced, an electrical signal from the temperature amplifier causes the torque motor in the control to override the mechanical schedule. From this point until military temperature is attained, the nozzle modulates according to a schedule determined by exhaust gas temperature and engine speed. This schedule permits rapid acceleration of the engine on a power lever burst. When military operation is reached, the temperature amplifier changes the signal to the torque motor and regulates nozzle area to maintain the desired steady state EGT.

The temperature amplifier receives a millivoltage from the engine thermocouples in order to derive the controlling signal that is

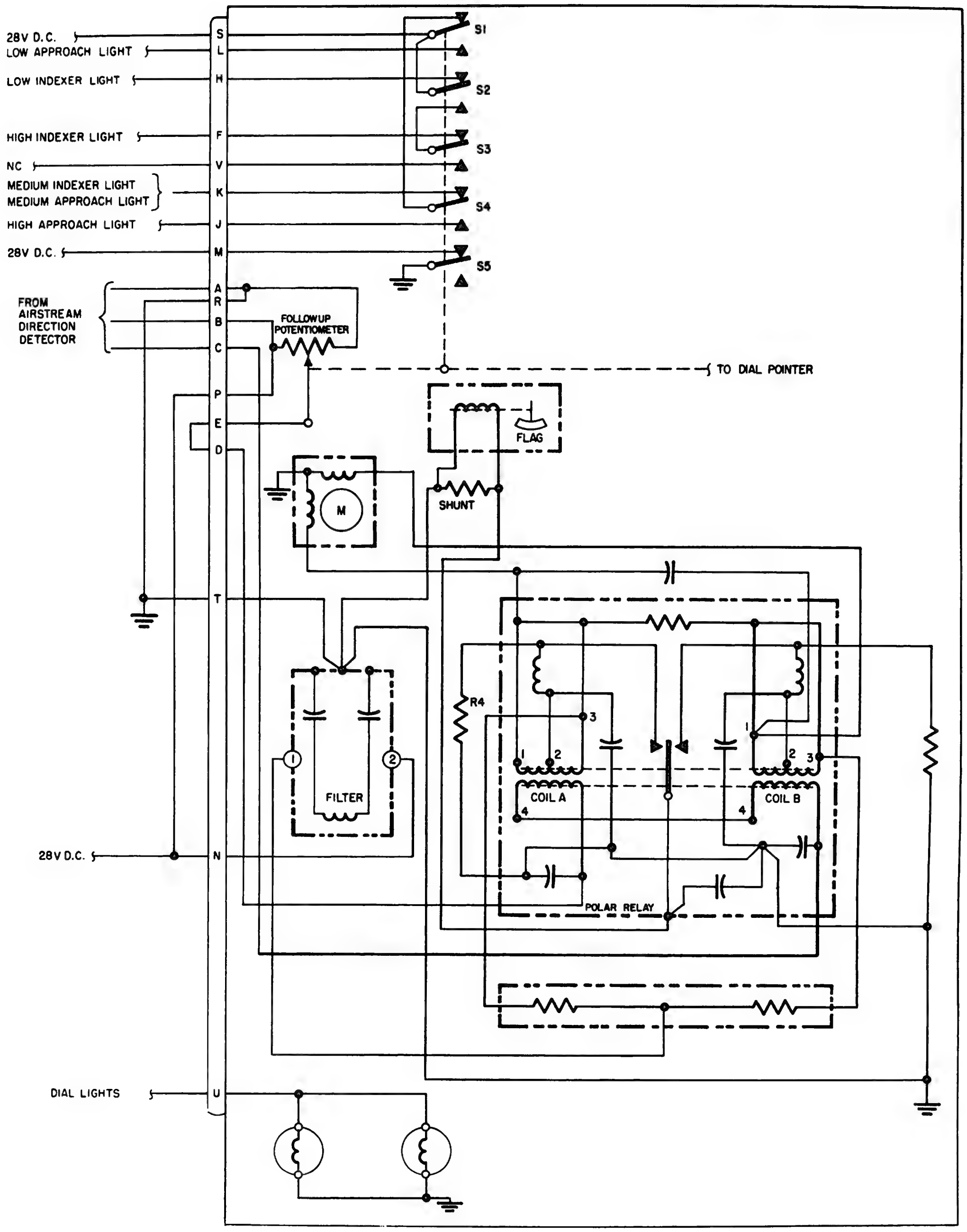

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Figure 12-17.—Angle-of-attack indicator schematic.

transmitted to the torque motor in the nozzle area control. The thermocouples measure the EGT after the exhaust gas exits from the thirdstage turbine wheel. A signal that varies with temperature is sent to the temperature amplifier, and another signal is sent to the exhaust gas temperature indicator in the cockpit. On an afterburner light, the rate of change of engine speed is sensed in the temperature amplifier through the frequency of the power that operates the amplifier.

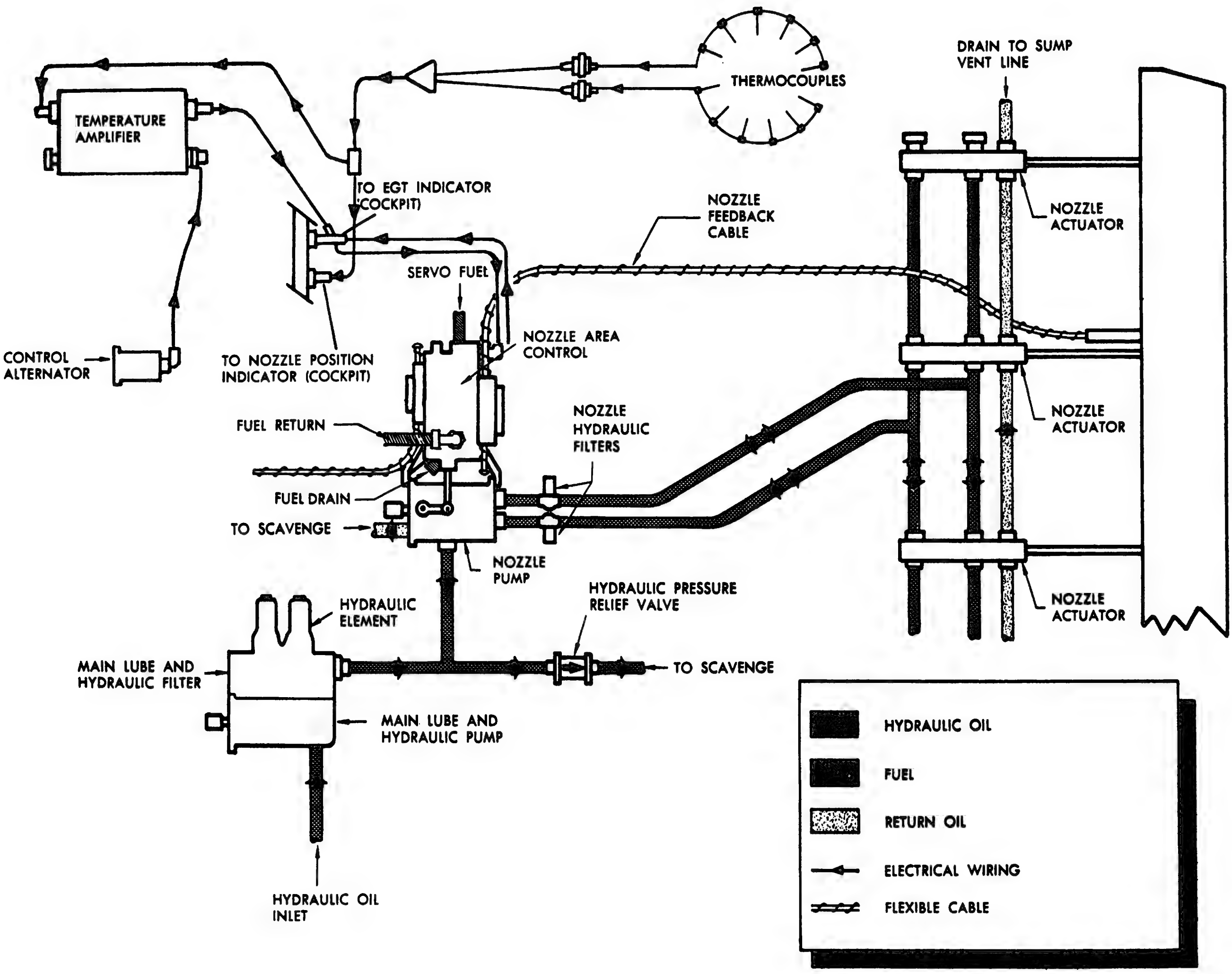

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Figure 12-18.—Variable nozzle system schematic.

This power is generated by the control alternator. A circuit in the amplifier modifies the signal to the torque motor according to the rate of change of engine speed. This modified signal schedules the nozzle open to reduce the speed rollback. A potentiometer, mounted on the nozzle feedback shaft in the nozzle area control, transmits a signal voltage of nozzle area to the nozzle position indicator in the cockpit.

The variable exhaust nozzle is a converging-diverging type nozzle which changes the exhaust escape area to control exhaust gas temperature and provide optimum thrust at all power settings. The assembly is composed of an internal primary nozzle of 24 flaps and an external secondary nozzle of 24 flaps. The flaps of the primary nozzle are hinged to the rear flange of the tailpipe. The secondary nozzle is secured by a stationary support shroud which is mounted onto the tailpipe by four brackets. The shroud is slotted to provide for thermal expansion and affords pivot points for the flap actuating mechanism. The primary and secondary flaps are linked together and controlled by four synchronized hydraulic actuators. When the flaps are in any position other than fully open, the primary flaps deflect the exhaust gases to a converging or narrowing stream. At the same time, secondary airflow along the outside of the engine is directed into the area between the

primary and secondary nozzles. This forms a cool air cushion on the inside of the secondary flaps and maintains convergence of the exhaust stream. When the nozzle is fully open, the primary flaps do not deflect the exhaust gases and the exhaust stream is unrestricted. For a given power setting, the exhaust gas temperature is increased by decreasing the nozzle area.

CONTROL ALTERNATOR

The control alternator generates the electrical power that is supplied to the temperature amplifier. The control alternator is a single-phase a-c generator with an 8-pole, permanent magnet rotor. The drive shaft is provided as part of the gearbox; therefore, the control alternator has no bearings and requires no lubrication. The stator winding is potted to protect the winding if oil leaks across the drive shaft seal. The control alternator is engine driven from the rear face of the transfer gearbox. Output voltage and frequency are proportional to engine speed.

THERMOCOUPLE HARNESS

Thermocouples convert heat energy from the engine exhaust gases into electrical signals which are used to indicate and control the engine operating temperature. The thermocouple harness consists of two half-sections. Each section contains six probe assemblies connected by formed, rigid piping. A probe assembly comprises a junction box, a harness mounting nut and flange, two loop-junction thermocouples, insulation and a housing to support the thermocouples wiring, and a cylindrical shield to protect the thermocouples.

One leg of the thermocouple wiring is Chromel wire and the other leg is Alumel wire. A loop-junction thermocouple is fabricated by welding together two small loops of these dissimilar metals. The assembled half-sections make up two independent thermocouple circuits, with each circuit consisting of 12 thermocouples connected in parallel. The harness is mounted on the turbine frame so that the probes extend into the exhaust gas flow slightly downstream from the No. 3 turbine wheel. Both Chromel and Alumel metals are electrical conductors, but they contain different amounts of free electrons. A thermocouple circuit is formed when these two metals are joined and the two junction points are exposed to different temperatures. If one junction, called the reference junction, is maintained at a known constant temperature and the second, or measuring junction (thermocouple), is heated, thermal agitation at the thermocouple causes the free electrons to move and develop a voltage output. This output is a linear function of temperature. In the thermocouple harness the thermocouples are combined into two circuits. The output of one circuit is routed to the temperature amplifier for use in controlling exhaust gas temperature. In this circuit the reference junction is located at the temperature amplifier connector. The second circuit supplies a signal to the exhaust gas temperature indicator in the cockpit.

TEMPERATURE AMPLIFIER

The temperature amplifier transmits an electrical signal to the torque motor in the nozzle area control. This signal varies according to changes of engine speed and exhaust gas temperature in order to actuate the mechanism of the nozzle area control which, in turn, schedules the area of the variable nozzle. During engine operation, fuel flows through a manifold on the underside of the amplifier to cool the internal components.

During the operation of the temperature amplifier, several separate units or modules inside the amplifier and two components outside the amplifier function to produce the final output signal that is transmitted to the torque motor.

The temperature amplifier is shown schematically in figure 12-19. The amplifier contains a power supply transformer, a rectifying and voltage regulating circuit and magnetic amplifiers to control the exhaust gas temperature. The thermocouple signal, which is a millivolt signal, is proportional to the exhaust gas temperature. This millivolt signal is fed into the amplifier at J1.

The control alternator supplies a voltage which is applied to the primary of the power transformer. The output of one secondary winding is rectified and used as a reference voltage. This voltage is regulated before and after rectification by a saturable reactor and a voltage regulating tube. The reference voltage is compared to the thermocouple signal; the difference is then amplified and a signal is sent out through J3 to the nozzle area control motor.

If the thermocouple voltage is less than the temperature reference voltage, a signal is sent to the nozzle area control causing the nozzle

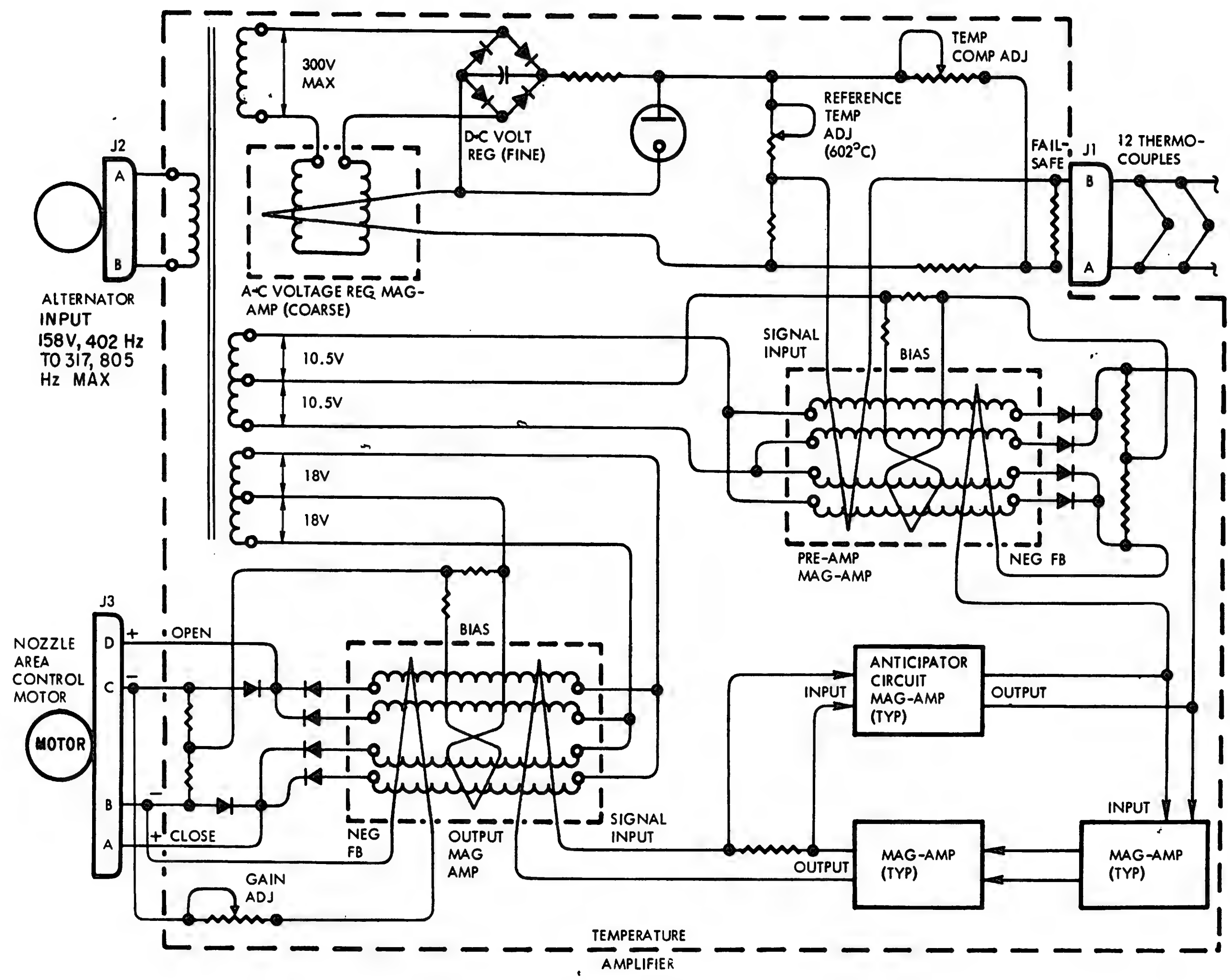

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Figure 12-19.—Schematic diagram of a temperature amplifier.

area to be decreased to the mechanical schedule of the control. If the thermocouple voltage is greater than the temperature reference voltage, the signal sent to the nozzle area control is of opposite polarity, and the nozzle area is increased.

A temperature compensating resistor in the thermocouple input circuit compensates for changes in ambient temperature. A resistor across the thermocouple input connection is a fail-safe feature in the event of an open circuit in the thermocouple harness. Should this occur, the resistor provides a complete path for the reference voltage, causing a cold signal which closes the nozzle to prevent a loss of engine thrust.

The testing of the variable nozzle system is discussed in chapter 14 of this manual.

AUTOMATIC TEMPERATURE CONTROL SYSTEMS

As previously mentioned, a control device is a device which governs in some predetermined manner the electric power delivered to an apparatus to which it is connected. An automatic temperature control system is an example of such a device. Automatic temperature control

systems are used on modern aircraft to control engine temperatures and cabin and vent suit temperatures.

Engine temperatures are usually controlled through the use of fuel trimming circuits, while cabin and vent suit temperatures are regulated through the use of sensors and transistorized bridge circuits. These two systems are discussed in greater detail in the following paragraphs.

ENGINE CONTROL SYSTEM

The engine control system permits the operator to control engine speed in the taxi range, turbine inlet temperature, and torque through the use of power and condition levers that are connected to each engine coordinator by pushrods, sectors, cables, and pulleys. When the engine is operating in the flight range, engine speed is constant. Engine power is controlled by increasing or decreasing fuel flow, which results in a corresponding change in turbine inlet temperature. The system installed in the E-2A aircraft is electromechanical and provides electronic fuel trimming.

The main components of the engine control system are as follows:

1. Power levers.
2. Condition levers.
3. Engine coordinators.
4. Temperature datum controls.
5. Turbine inlet thermocouples.
6. Temperature datum switches.

The block diagram of an engine control system is shown in figure 12-20.

Power Levers

The power levers (one for each engine) can be moved separately or both at the same time to control engine power, within a range of settings from REVERSE (reverse thrust) to MAX POWER (takeoff). (See fig. 12-20.) Switches within the cockpit pedestal are actuated by the power levers to supply electircal power to other systems. A detent at the FLT IDLE position prevents inadvertent movement of the power levers below FLT IDLE. To move the power levers to the taxi range, the levers must be raised from the detent. During a catapult-assisted takeoff, a retractable catapult grip aids the pilot in maintaining the power levers at MAX POWER.

Condition Levers

The condition levers (fig. 12-20) are next to the power levers on the cockpit pedestal and have FEATH, GRD STOP, RUN, and AIRSTART positions. Switches actuated at each condition lever position complete electrical circuits for other systems. Each condition lever has a detent release handle which must be lifted to move the levers to different positions. A detent holds the lever at FEATH, GRD STOP, or RUN. When the condition lever AIR START position is selected, the propeller unfeathers and the engine starting cycle begins. The lever must be held in the AIR START position until the engine speed reaches 100 percent rpm; when released, the lever springs back to RUN and remains there for all normal operation. When set to RUN, the condition lever positions the mechanical linkage to open the fuel shutoff valve. A mechanical stop in the pedestal prevents both condition levers from being set to FEATH at the same time. When set to FEATH, the condition lever electrically and mechanically closes the corresponding fuel shutoff valve and feathers the propeller. At GRD STOP, the condition lever electrically closes the fuel shutoff valve to shutdown the engine.

Engine Coordinators.

The coordinators (fig. 12-20) are mechanical devices that coordinate the power and condition levers, the propeller, the fuel control, and the electronic fuel trimming circuit. One engine coordinator is mounted on each fuel control. The main components of a coordinator are a variable potentiometer, a discriminating device, and a cam-operated switch. A scale calibrated from 0° to 90° is attached to the outside case; a pointer is secured to the main coordinator shaft. Pushrods connected from the coordinator to a cable sector transmit power and condition lever movement to the coordinator. Power lever movement transmitted to the coordinator changes the resistance of the variable potentiometer and changes the desired temperature reference signal to the temperature datum control. The cam-operated switch switches the temperature datum control from temperature limiting to temperature controlling when the power lever is moved above 66° coordinator indication and if engine speed is above 94 percent rpm. Movement of the power level is transmitted to the coordinator and then to the propeller and fuel control

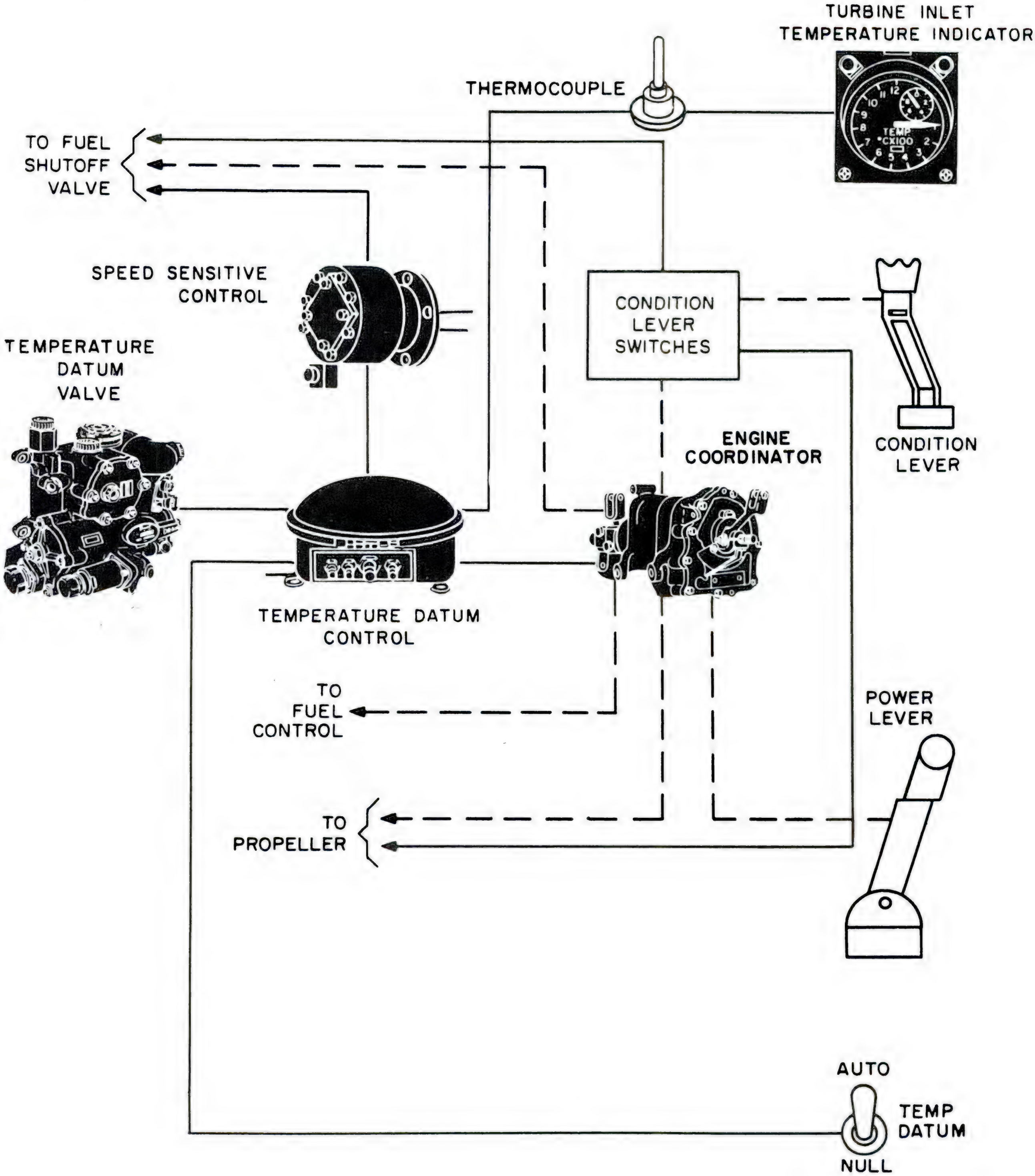

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Figure 12-20.—Engine control system block diagram.

through a series of rods and levers. When the condition lever is moved to FEATH, the discriminating device mechanically positions the propeller linkage toward feather and closes the fuel shutoff valve in the fuel control, regardless of power lever setting.

Temperature Datum Controls

The temperature datum controls (fig. 12-20) are electronic units that automatically compensate for changes in fuel density, manufacturing tolerances in fuel controls, and variations in engine fuel requirements between engines. With the power lever above 66° coordinator (temperature controlling range) and the TEMP DATUM switch in AUTO, the temperature datum control compares the actual turbine inlet temperature signal and the desired temperature reference signal. If the difference is greater than 1.9° C (4.5° F), the control electrically signals the temperature datum valve to reduce or increase fuel flow to the engine, as required, to bring the turbine inlet temperature to the desired value. A damping voltage is fed back to the control from a generator within the temperature valve motor to prevent overcorrection and stabilize the system. When the engine speed is above 94 percent rpm and the power lever is below 66° coordinator (temperature limiting range), the normal limiting temperature (maximum power) is automatically set at 978° C (1,792° F). However, when the engine speed is below 94 percent rpm regardless of power lever position, the limiting temperature is set at 830° C (1,525° F) to prevent excessive turbine inlet temperature during starting and acceleration when the compressor bleed valves are open.

Turbine Inlet Thermocouples

Dual-unit thermocouples (fig. 12-20) are radially mounted in the turbine inlet case of each engine. The junction portion of the thermocouples protrudes through the case to sense the gas temperature before the gas enters the turbine section. Four leads, two of Chromel and two of Alumel, connect to each thermocouple to form two independent parallel circuits. One circuit is connected to the cockpit turbine inlet temperature indicator; the other circuit supplies the temperature datum control with temperature signals for the electronic fuel trimming circuit. As the gases heat the thermocouples, an electromotive force created in the thermocouples is transmitted through the connecting wiring harness to the cockpit indicator and the temperature datum control. Because the thermocouples are wired in parallel, the average temperature of the thermocouples is transmitted. If one parallel circuit fails, the other circuit is not affected.

Temperature Datum Switches

The left and right engine temperature datum (TEMP DATUM) switches are on the engine control panel in the cockpit. Each switch has AUTO and NULL positions. (See fig. 12-20.) When the switch is set to AUTO (the electronic fuel trimming circuit is operating in the temperature-controlling range), the temperature datum control compares the turbine inlet temperature (represented by the output of the turbine inlet thermocouples) to a reference temperature (represented by the output of the potentiometer in the coordinator). If the temperatures differ, the temperature datum control electrically signals the temperature datum valve to bypass more or less fuel from the engine to keep turbine inlet temperature at the selected value.

If the electronic fuel trimming circuit malfunctions, the TEMP DATUM switch must be set to NULL. The circuit is thereby deenergized and turbine inlet temperature is controlled by the fuel control through movement of the power lever. Overtemperature protection is locked out and the turbine inlet temperature indicator must be continually monitored to prevent excessive turbine inlet temperatures.

CABIN AND VENT SUIT TEMPERATURE CONTROL SYSTEM

The cabin and vent suit temperature controller is a transistorized electronic device that operates on 120 v, 400 Hz a.c. Maximum power consumption is 28 watts.

Electrically, the controller consists of two channels: the cabin temperature channel and the ventilated suit channel. Both channels operate in basically the same manner: bridge circuits compare temperature selector and temperature sensor resistances, which are representative of selected and actual temperature conditions, and generate a resultant d-c error voltage. The d-c error voltage is then modulated and amplified. The resulting a-c signal is the output of the controller and has phase and voltage characteristics, proportional to the

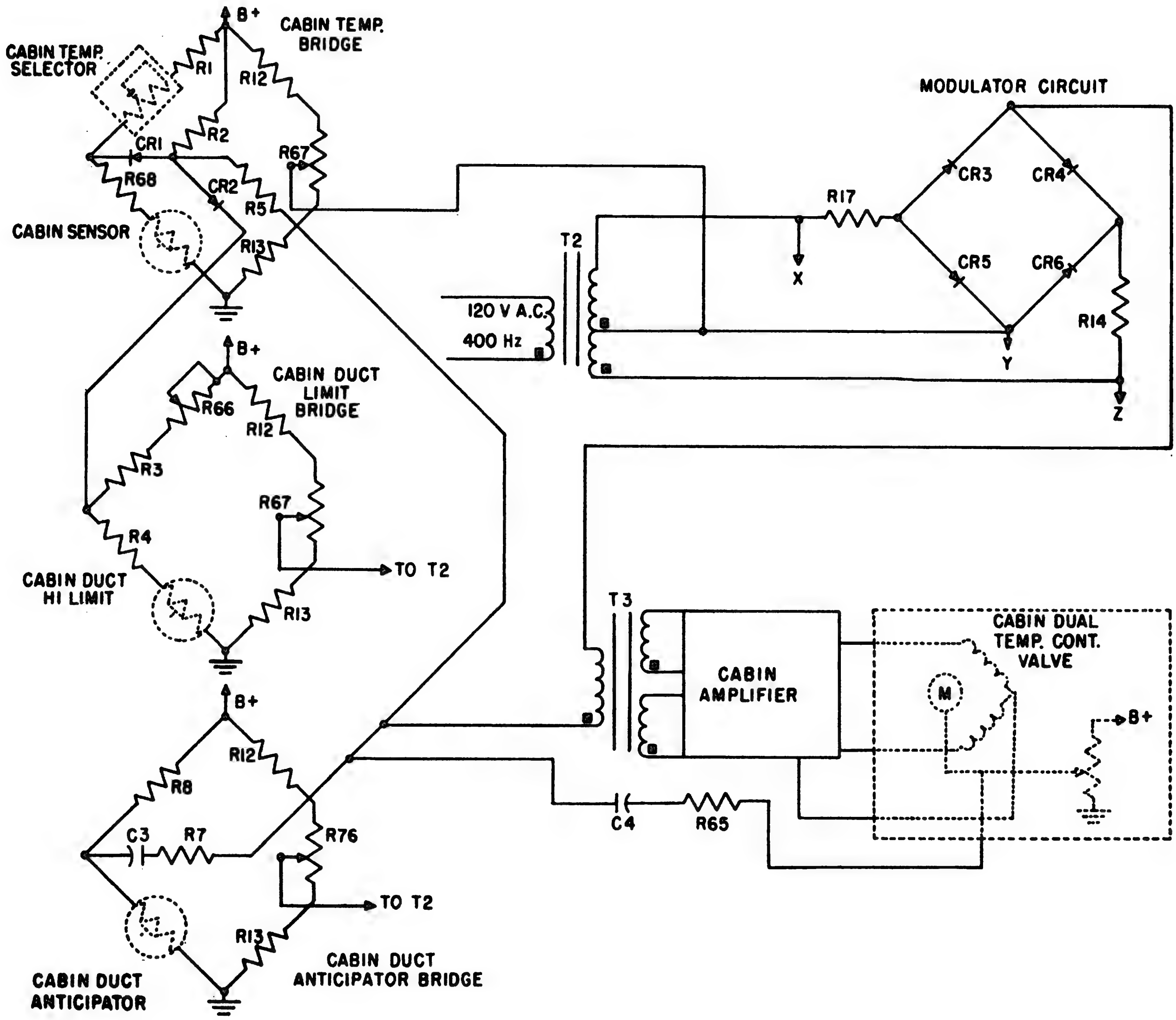

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Figure 12-21.—Cabin temperature channel.

magnitude of the d-c error signal. It is fed to the 2-phase servomotor of the appropriate control valve to continuously actuate the valve to maintain the selected temperature.

The cabin temperature channel of the temperature controller utilizes three bridge circuits to maintain cabin temperature. (See fig. 12-21.) Selection of the desired temperature with the cabin temperature selector varies resistance of one leg of the cabin temperature bridge. The varying cabin temperature varies the resistance of the cabin sensor in the second leg of the bridge circuit. Thus, a selected temperature must be accompanied by a change of cabin temperature to provide bridge balance between the cabin sensor and selector. Whenever bridge imbalance exists, the resulting d-c voltage is a-c modulated by the modulator circuit, amplified by the cabin amplifier, and fed to the control valve servomotor to either increase or decrease cabin temperature.

The function of the cabin duct limit bridge is to limit the temperature of the cabin inlet air. A diode biasing network permits the cabin

duct limit bridge to override the cabin temperature bridge when the duct temperature limit is attained. The resulting d-c voltage is fed to the modulator circuit, to the cabin amplifier, and to the control valve servomotor to decrease cabin temperature.

The cabin duct anticipator bridge functions with sudden changes of air temperature in the cabin air inlet duct. This is accomplished by capacitor-coupling the error voltage to the modulator. When the cabin temperature is being held at the selected temperature with constant cabin inlet air temperatures, the anticipator bridge is in balance. Should duct temperature suddenly increase or decrease with all other conditions remaining the same, the anticipator bridge is unbalanced and an error voltage is supplied to the modulator circuit. The resulting amplified signal regulates the cabin control valve to return the duct air to its original temperature. Error voltages caused by imbalance of the cabin temperature or cabin duct limit bridges override the cabin duct anticipator bridge, provided the duct air temperature error is gradual or small.

One additional error voltage is capacitor-coupled to the modulator circuit. It is the voltage change that is proportionate to the rate of change of the feedback potentiometer of the cabin dual temperature control valve. This voltage change is applicable only when the valve is being regulated (the feedback potentiometer is rotating). Therefore, the error feedback voltage seen at the input of the control is proportionate to the rate of change of the feedback potentiometer. Once regulation of the valve has started, the rate-of-change voltage from the potentiometer reduces the initial starting voltage to the control valve actuator motor, thus slowing valve actuator rotation.

The ventilated suit channel of the temperature controller utilizes but one bridge circuit to maintain suit temperature. (See fig. 12-22.) The operation of this bridge is similar to that of the cabin temperature bridge. The suit temperature selector resistance in one leg is balanced against the suit duct temperature sensor resistance in the opposite leg. Imbalance between these legs of the suit temperature bridge results in a d-c error voltage, which is a-c modulated

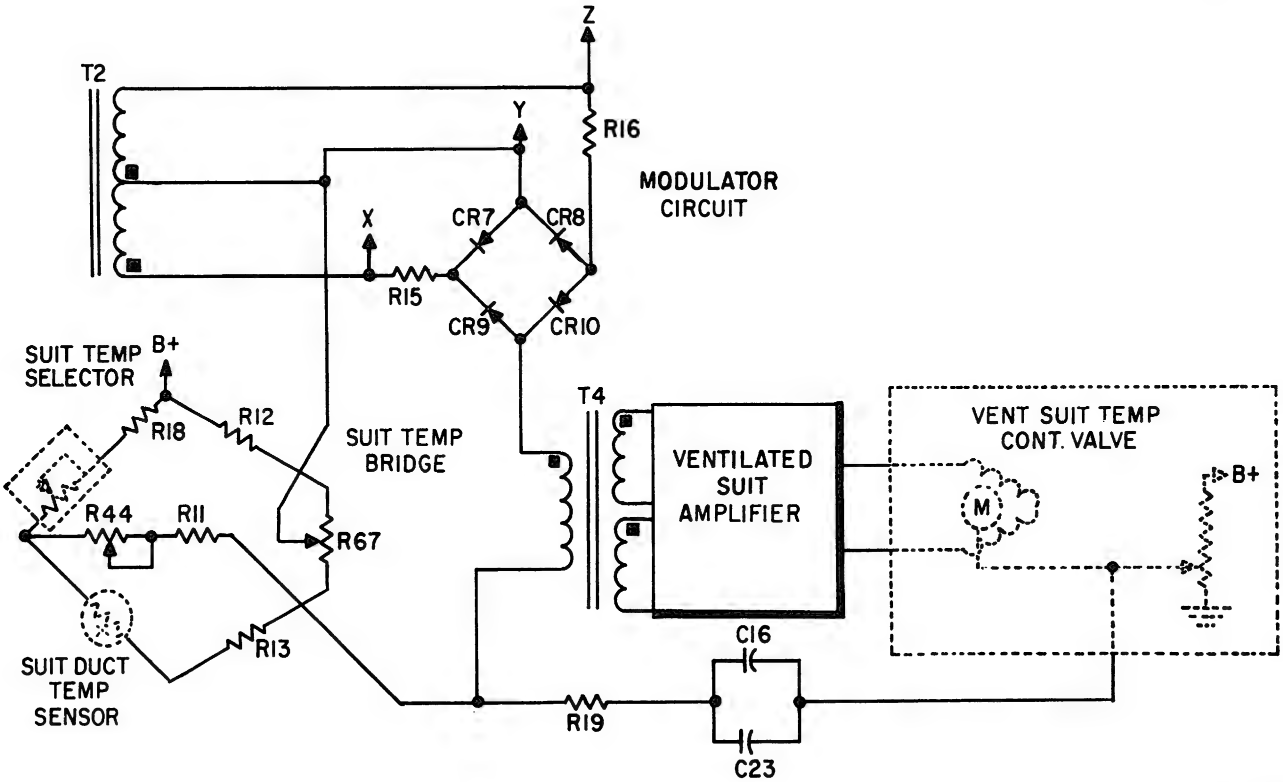

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Figure 12-22.—Vent suit channel.

by the modulator circuit, amplified, and applied to the suit temperature control valve to alter suit air temperatures.

Rate-of-change voltage from the feedback potentiometer in the ventilated suit temperature control valve is capacitance-coupled to the modulator circuit. As in the cabin temperature channel, this voltage is applicable only when the valve is being actuated. It reduces the initial starting voltage to the valve once actuator rotation has started, thus slowing actuator rotation.

PRESSURIZATION AND AIR CONDITIONING

The air-conditioning and pressurization systems of modern aircraft require the cabin and equipment be maintained at a pressure altitude and temperature control level during high altitude flight.

The system supplies conditioned air for heating and cooling the cabin, crew spaces, and various electronic equipment.

The majority of the air-conditioning systems installed in modern aircraft utilize the air cycle system. Some aircraft utilize the vapor cycle system, which uses a liquid Freon similar to that used in a common household refrigerator. The operation of the air cycle and vapor cycle systems are discussed in chapter 15 of AE 3 & 2 NavPers 10348-C.

A brief discussion of the cabin and equipment air-conditioning and pressurization system installed in the A-6A aircraft is presented in the following paragraphs.

CABIN SYSTEM

The primary function of the cabin air-conditioning and pressurization system is to maintain cockpit temperature and pressure within the limits of crew safety and comfort. To accomplish this, the system forces a mixture of dehumidified refrigerated air and hot engine bleed air through cockpit diffusers. The temperature of the mixture is automatically maintained through a continuously selective range by a temperature control system consisting of temperature sensors with associated flow control valves and an electronic controller. Cabin pressure is controlled by a pressure regulator and a safety valve, with a manual dump control associated with the safety valve. The block diagram for the airflow of the cabin air-conditioning and pressurization system is shown in figure 12-23.

System Operation

Placing the cockpit switch ON (fig. 12-24) breaks the circuit from the 28-volt d-c primary bus, through the canopy switches to the cabin bleed air shutoff valve, and the valve opens. Simultaneously, a second portion of the cockpit switch, which is ganged to the first, completes the circuit from the cabin duct thermal switch through the cockpit switch to the dual temperature control valve. The third portion of the cockpit switch closes, completing the circuit from the 120 volt a-c essential bus through the LAT/LONG circuit breakers to the air-conditioning relay. The relay is energized, completing the air-conditioning circuits as it opens the ram air circuits.

In the air-conditioning mode (cockpit switch ON), hot engine bleed air flows through the cabin shutoff valve to the dual temperature control valve where it is mixed with refrigerated, dehumidified air. The cabin temperature control system automatically maintains the cabin at a selected temperature by continuously modulating the dual temperature control valve. The modulating signals are cabin temperature errors that are translated into error voltages by the cabin temperature sensor. These signals are modulated and amplified by the cabin and ventilation suit temperature controller, and transmitted to the control winding of the dual temperature control valve; the hot side of the valve starts to close, and the cold side opens until the selected cabin temperature is achieved. In order to prevent temperature hunting by the cabin temperature sensor, the cabin duct dual temperature sensor anticipates changes in cabin temperature by sensing changes in the duct inlet temperature.

The dual temperature sensor transmits error signals to the cabin and ventilation suit temperature controller whenever the temperature of the cabin air supply changes. The magnitude of the transmitted signals depends upon the rate of temperature change. When the cabin duct inlet temperature exceeds 121.1° C (250° F), the overtemperature sensor portion of this sensor transmits a fixed signal through the temperature controller to the control winding of the dual temperature control valve. The valve is driven to the full cold position until the duct temperature returns to normal, and automatic control is resumed.

An additional override to the cabin temperature sensor is provided by the cabin duct thermal switch. This temperature-sensitive switch

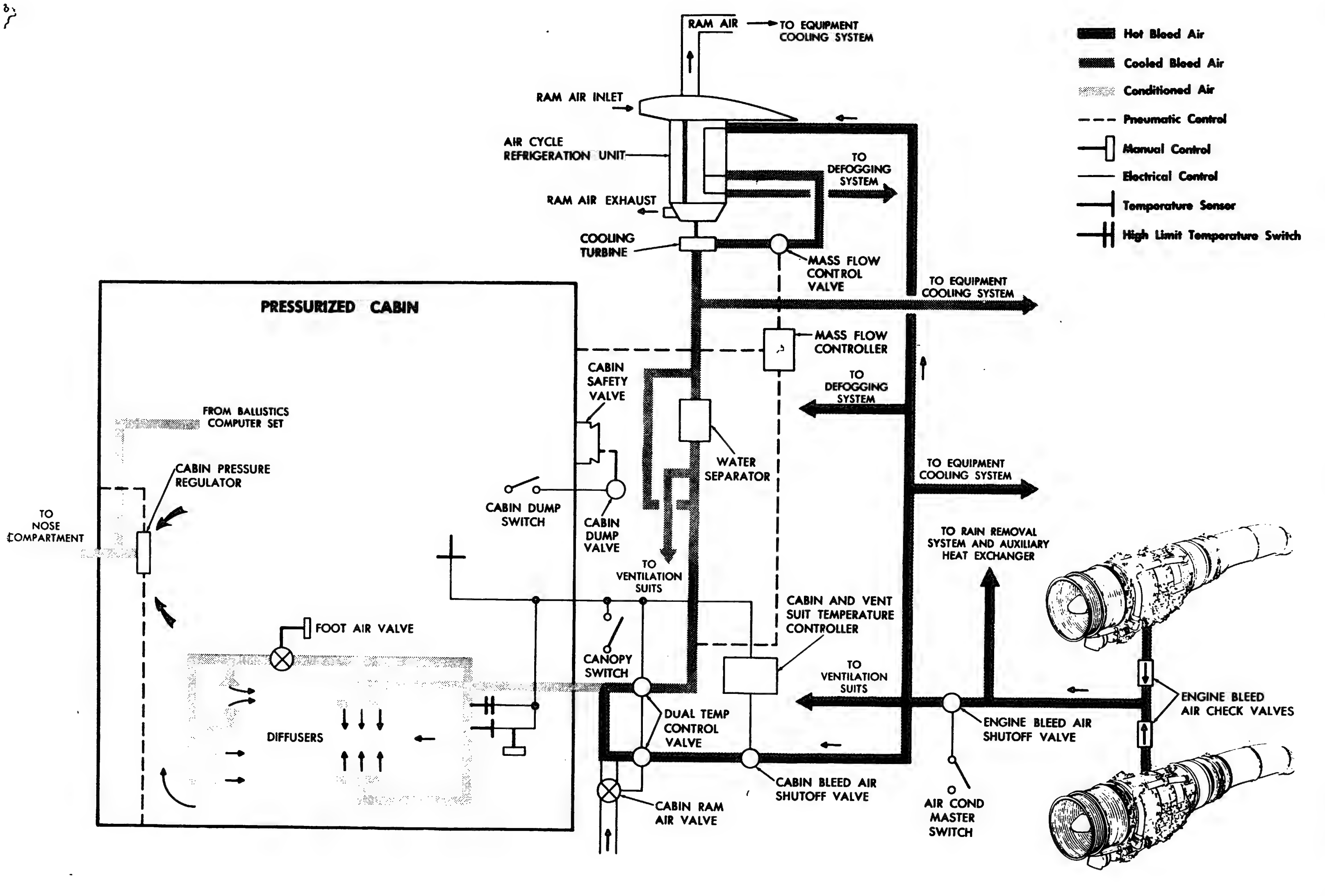


Figure 12-23.—Cabin air-conditioning and pressurization diagram.

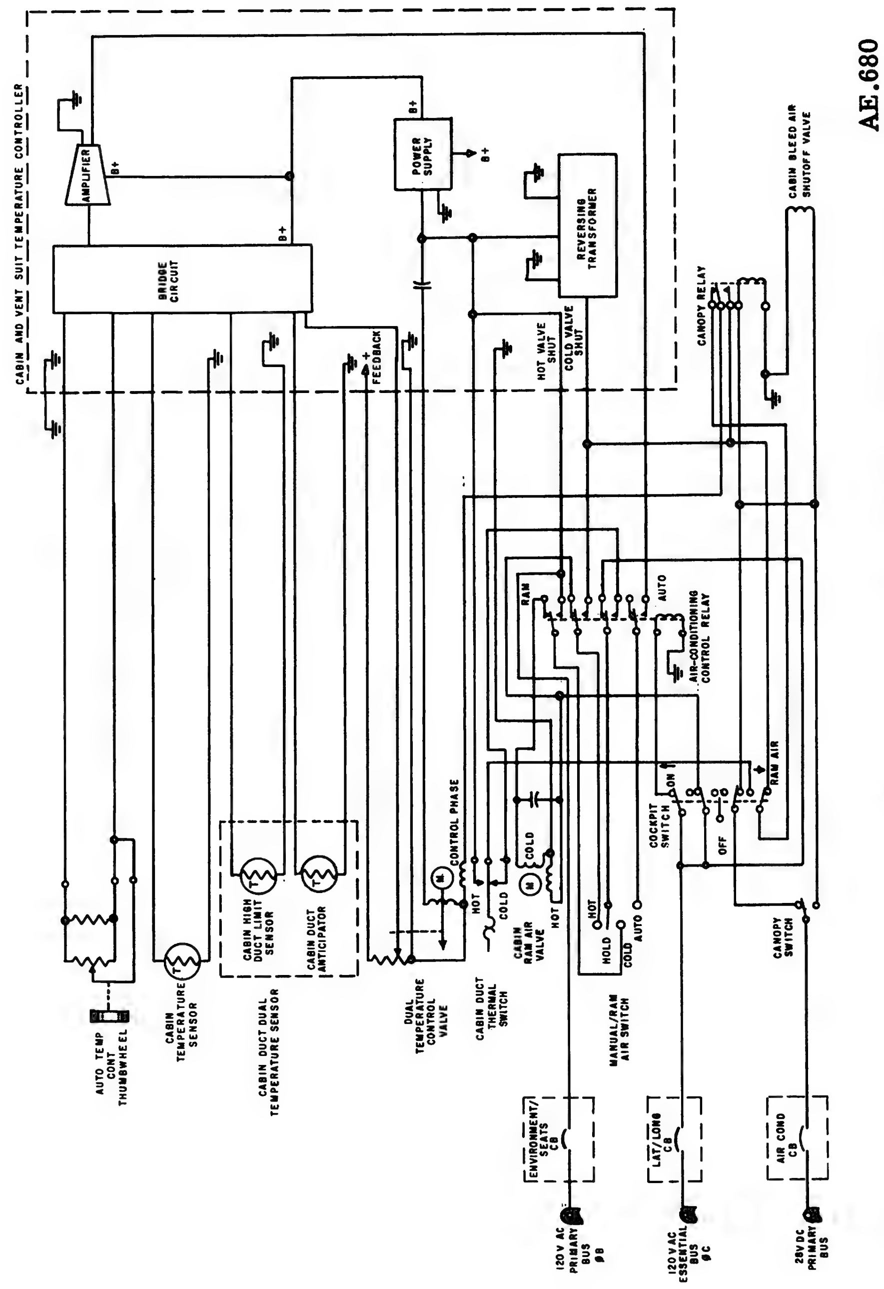


Figure 12-24.—Cabin air-conditioning and pressurization schematic diagram.

closes when the duct inlet temperature exceeds 121.1° C (250° F) or the dual temperature sensor malfunctions. During these conditions a fixed a-c signal is transmitted through the cockpit switch to the control winding of the dual temperature control valve driving actuator, cycling the valve to the full cold position. When the cabin duct inlet temperature is reduced to 121.1° C (250° F), the switch opens and automatic temperature control is resumed.

In the automatic mode, cockpit temperature is selected by positioning the AUTO TEMP CONT thumbwheel. This fixes the output voltage of the bridge circuit in the cabin and ventilation suit controller. The signal is amplified in the controller and transmitted through the air-conditioning relay to the MAN/RAM AIR switch. When this switch is at AUTO, the signal travels back through the air-conditioning relay to the cold side of the cabin thermal switch.

Manual control of the cabin air-conditioning system is acquired by momentarily positioning the MAN/RAM AIR switch at COLD or HOT. At COLD, the circuit is completed, and 120 volt a.c. flows through the air-conditioning relay, the thermal switch, the cockpit switch, the reversing transformer, and the dual temperature control valve driving actuator. The cold side of the valve starts to open, and the hot side closes until the MAN/RAM AIR switch is released. The switch returns to HOLD, and the valve remains fixed. Holding the MAN/RAM AIR switch at HOT completes the circuit from the 120-volt primary bus through the ENVIRONMENT/SEATS circuit breaker through the reversing transformer, the air-conditioning relay, and the MAN/RAM AIR switch. The 120-volt signal then passes back through the air-conditioning relay, the cabin duct thermal switch, the cockpit switch, and the canopy switch to the control winding on the dual temperature control valve. The hot side of the valve starts to open, and the cold side closes until the switch is released, and the valve remains fixed.

Under any of the previously described conditions—in either the automatic or manual mode—failure of electrical power to the cabin and ventilation suit temperature controller or to the dual temperature control valve will cause the valve to fail fixed in the position it was maintaining at the time of electrical failure. When the canopy is opened and either automatic or manual temperature control is in effect, the canopy relay and canopy switch will close the cabin bleed air shutoff valve and drive the dual temperature control valve into the full hot position.

The cabin may be ram air ventilated by placing the cockpit switch at RAM AIR. With the canopy closed, this action deenergizes the air-conditioning control relay, closes the cabin bleed air shutoff valve and drives the dual temperature control valve to the full hot position, effectively blocking the flow of both hot and cold bleed air to the cabin. Either crewmember may control the degree of ram air ventilation by depressing the MAN/RAM AIR switch to either HOT or COLD. The HOT position drives the cabin ram air valve toward the closed position, restricting the ram air flow, and the COLD position drives the cabin ram air valve toward the open position, increasing the ram air flow. Any position of the cabin ram air valve from full open to full closed may be selected.

Cabin pressurization is automatically initiated at 8,000 feet; the cabin pressure is maintained at 8,000 feet until a pressure differential of 5 psi is reached. Thereafter, the pressure differential is maintained at 5 psi.

The preceding pressure schedule is maintained by the cabin pressure regulator. This valve allows the air passed into the cabin air-conditioning system to exhaust into the nose compartment. From sea level to 8,000 feet, the exhaust flow is unrestricted. Above 8,000 feet, the valve closes down, restricting the exhaust flow until a cabin pressure quivalent to 8,000 feet altitude is maintained. The cabin remains at this pressure as the aircraft climbs until a cabin-to-ambient pressure differential of 5 psi is reached. Beyond this altitude, the valve regulates the exhaust flow to maintain this constant pressure differential throughout the remaining altitude range.

A cabin pressure safety valve is provided to limit cabin pressure in the event of regulator malfunction. This valve limits the cabin-to-ambient pressure differential to 5.5 psi. The CABIN DUMP switch permits either crewmenber to dump cabin pressure through the cabin safety valve. Placing the CABIN DUMP switch at ON completes a circuit to the solenoid on the cabin dump valve which opens the cabin safety valve.

EQUIPMENT COOLING SYSTEM

The equipment cooling system cools electronic equipment by means of ram air. Ram air is the primary means of ventilation for the

forward and aft equipment compartments. Ventilation of these compartments is controlled by the ram air thermal switch, the equipment cooling valve, the forward compartment ram air valve, and the aft compartment ram air valve.

When the aircraft is in flight, the equipment cooling valve is closed and the forward and aft compartment ram air valves are open. Under these conditions, the right forward and aft equipment compartments are ram air ventilated. When the temperature in the right wing ram air duct reaches 46.1° C (115° F), the equipment cooling valve opens and the forward and aft compartment ram air valves close. This permits moist, cooled bleed air to flow into the right forward and aft equipment compartments and insures adequate cooling when ambient air temperatures are excessive.

The equipment cooling system flow diagram is shown in figure 12-25.

System Operation

With an engine running, the equipment cooling system is automatically engaged when the AIR COND MASTER switch is placed at NORM. (See fig. 12-26.) Under these conditions, the circuit from the 28-volt d-c essential bus through the AIR COND circuit breaker to the solenoid of the engine bleed air shutoff valve is complete, and bleed air flows to the air cycle refrigeration unit. The discharge from the cooling turbine supplies the cooled bleed air used by the equipment cooling system.

When the aircraft is airborne, and the ram air temperature is below 46.1° C (115° F), voltage from the 120-volt primary bus is fed through the EQUIP COOL circuit breaker, the overpressurization relay, and the unoperated ram air thermal switch to the equipment cooling valve, the forward compartment ram air valve, and the aft compartment ram air valve. The equipment cooling valve is operated to the fully closed position and the forward compartment and aft compartment ram air valves are operated to the fully open position. Ram air flows to the right forward and aft equipment compartments and the cooled bleed airflow is shut off.

When the ram air temperature exceeds 46.1° C (115° F), the ram air thermal switch operates. Voltage from the 120-volt primary bus is fed through the EQUIP COOL circuit breaker, the overpressurization relay, and the operated ram air thermal switch to the equipment cooling valve, the forward compartment ram air valve, and the aft compartment ram air valve. The equipment cooling valve is operated to the fully open position and the forward compartment and aft compartment ram air valves are operated to the fully closed position. Undried, cooled bleed air flows to the forward and aft equipment compartments and the ram air to these compartments is shut off.

When an overpressurization condition occurs, the pressure switch operates, closing the overpressurization relay. Voltage from the 120-volt primary bus is fed through the EQUIP COOL circuit breaker and the overpressurization relay to the equipment cooling valve, the forward compartment ram air valve, and the aft compartment ram air valve. The equipment cooling valve is operated to the fully open position and the forward and aft compartment ram air valves are operated to the fully closed position. Under these conditions, the overpressure is dumped into the forward and aft equipment compartments.

The computer pressure regulator maintains a pressure of 2 to 3 psi in the equipment cooling line. The pressure regulated, partially-dried cooled bleed air from the regulator is automatically mixed with controlled quantities of hot bleed air by the servocontrolled computer temperature control valve. This valve modulates in response to temperature signals sensed in the computer inlet duct the by the computer temperature sensor to maintain a fixed computer duct temperature of 4.4° ± 2.8° C (40° ± 5° F). The temperature controlled air flows through the Ballistics Computer Set. Sonic venturis located in the ballistics computer outlet duct and the transmitter modulator inlet duct limits the flow of cooling air.

A safety override for the computer temperature control valve is provided by including the computer cooling shutoff valve upstream of the computer temperature control valve. If the computer duct temperature exceeds 65.6° C (150° F), the computer thermal switch opens, deenergizing the computer overheat indicator relay and completing the circuit to the COMPUTER OVERHEAT caution light. Voltage from the 28-volt essential d-c bus is fed through the AIR COND circuit breaker and the computer overheat indicator relay to energize the computer cooling control relay thereby deenergizing and closing the computer cooling shutoff valve. If the computer duct temperature drops below 65.6° C (150° F), the contacts of the computer thermal switch close, energizing the computer overheat

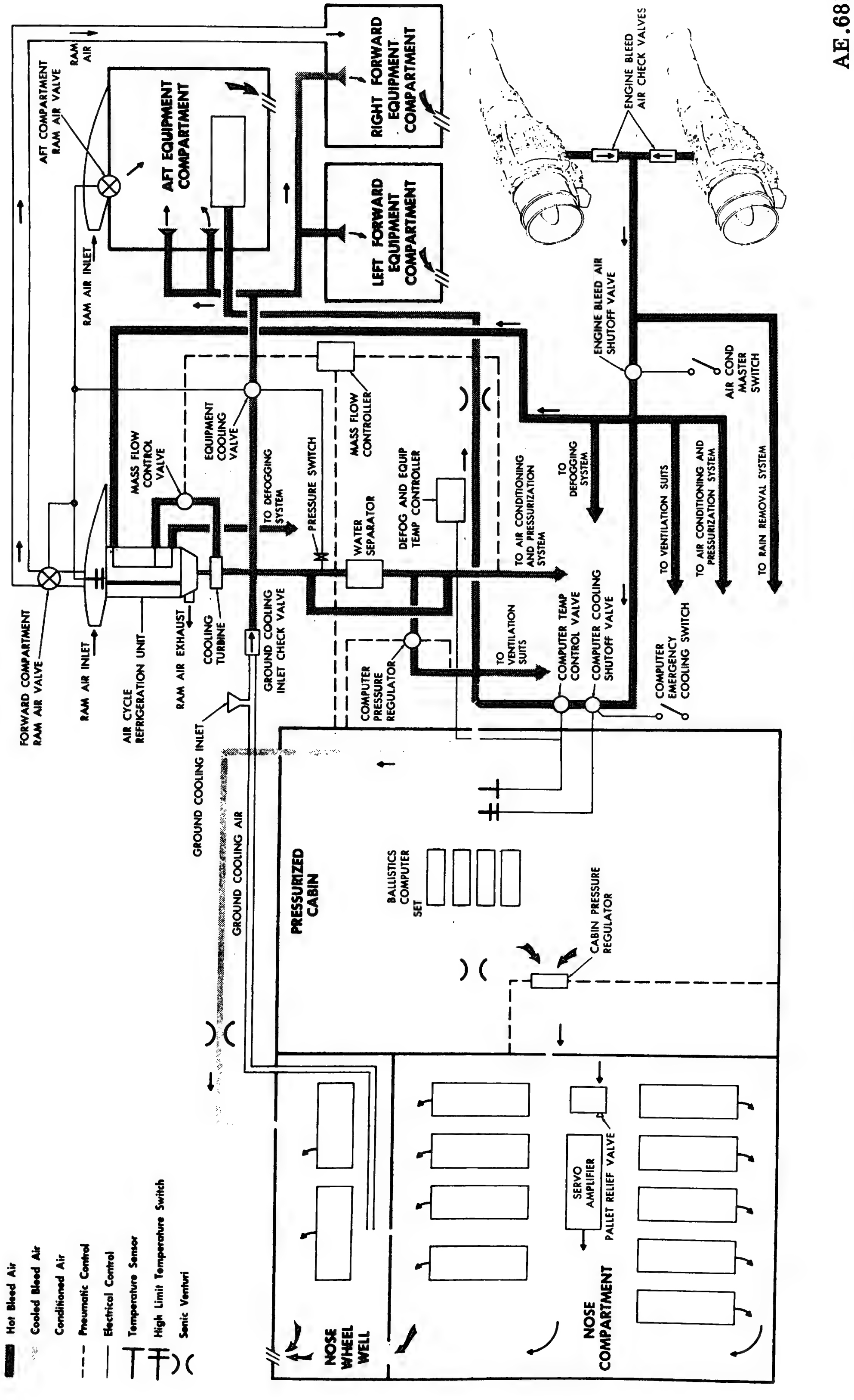


Figure 12-25.—Equipment cooling flow diagram.

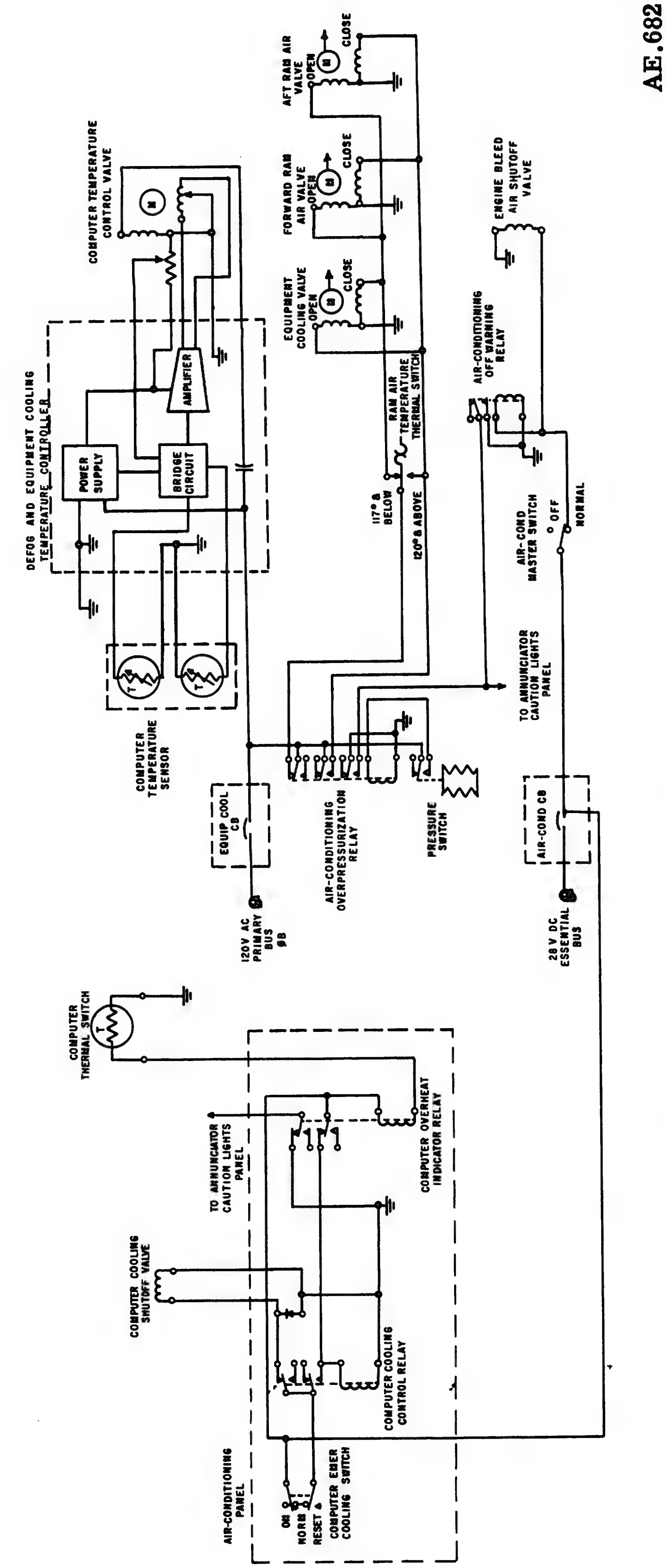


Figure 12-26.—Equipment cooling schematic diagram.

indicator relay and interrupts the circuit to the COMPUTER OVERHEAT caution light. The computer cooling control relay remains energized through the computer emergency cooling switch and its own contacts. By momentarily placing the CMPTR EMER COOL switch to RESET, the computer cooling control relay becomes deenergized completing the circuit to open the computer cooling shutoff valve. If the COMPUTER OVERHEAT caution light should cycle on and off indicating a constant overheat condition, the computer cooling shutoff valve can be permanently closed by placing the CMPTR EMER COOL switch at ON. This will allow uncontrolled cooled bleed air to be ducted to the Ballistics Computer.

Air exhausted from Ballistics Computer Set and from the cockpit is circulated through the less critical electronic equipments compartments. The direct cooling requirements of the CNI equipment in the aft equipment compartment are supplied by dehumidified, pressure-regulated air tapped downstream of the computer pressure regulator.

CHAPTER 13
PROPELLER SYNCHRONIZATION

The advances in the development of turbojet engines in recent years has made it possible for jetpropelled aircraft to replace propeller-driven aircraft in almost every type of mission. Yet, propeller-driven aircraft are better suited to perform such missions as long-range patrols, antisubmarine warfare, and short-runway landings and takeoffs. Because the Navy has a continuing need for propeller-driven aircraft, the AE has a need for understanding principles of propeller controls.

Although the AE need not be concerned with mechanical maintenance of propellers and their governors, it is advisable that he at least understand their fundamental principles of operation, for an understanding of the mechanics of the system aids in his understanding the functions of the controlling circuits. Since all of the mechanical operations of propellers are not covered in this manual, it is suggested that the reader refer to the appropriate chapter in the Rate Training Manual, Aviation Machinist's Mate R 3 & 2, or other available sources for background information.

The purpose of this chapter is to explain the electrical operation of controlling and synchronizing hydromatic propellers of multi-engine aircraft. The discussion will cover propeller governor action for controlling engine rpm, propeller feathering and unfeathering, propeller reversing and unreversing, and for maintaining multiengine synchronous speed for propellers common to P-2 and C-118 aircraft. Propeller synchrophasing, which is common to P-3 and C-130 aircraft, is also discussed in the latter part of this chapter.

At this point, it should be understood that there is a difference between synchronizing engine rpm and synchrophasing propellers in that propeller synchrophasing is a better quality engine synchronization. Before corrections can be initiated in the synchronizing system, there must be a difference in engine rpm, while the synchrophasing system can correct for a difference in degrees of engine rpm.

DOUBLE-ACTING GOVERNOR

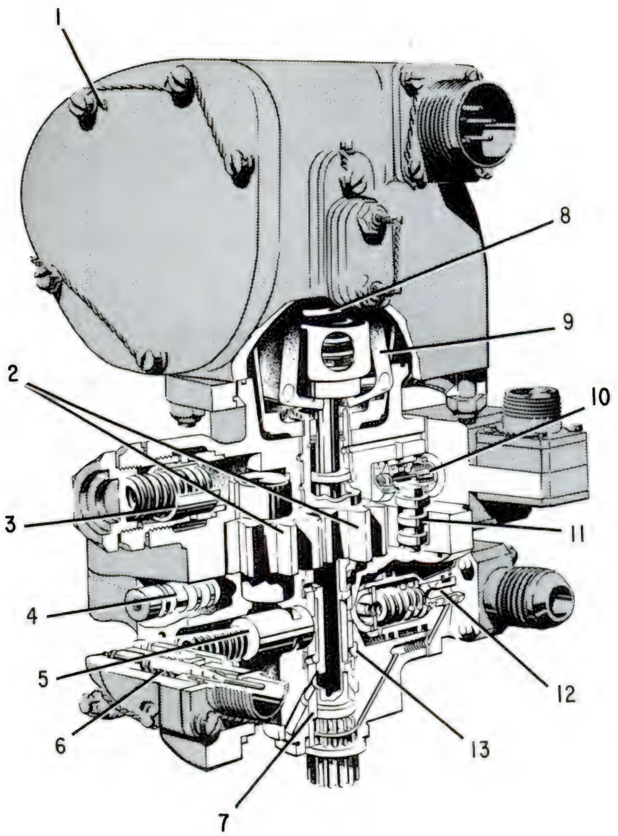
A propeller governor is a control device that is used to control engine speed by varying the pitch of the propeller. Increasing the propeller pitch adds load on the engine in terms of increased thrust of the propeller, thereby reducing engine speed; conversely, decreasing the propeller pitch reduces engine load and therefore increases its speed. Hence, engine speed is a function of propeller pitch. Furthermore, if the propeller governor setting remains unchanged, any variation of power produced by the engine is translated into a corresponding variation of propeller thrust by varying the propeller pitch while engine speed remains constant. Optimum efficiency of an engine is best realized when its speed is constant; therefore, the propeller governor serves in achieving engine efficiency.

The pitch of hydromatic propeller blades is varied hydraulically by porting engine lubricating oil that has been boosted to the required pressure onto the propeller piston which is located in the propeller dome. The action on the piston is transmitted through a geared cam mechanism which rotates the propeller blades to the pitch desired.

The double-acting governor, (fig. 13-1) is the constant speed control device used in conjunction with the hydromatic propeller discussed in this chapter. The descriptive term "double-acting" is derived from the fact that the output oil of the pump can be directed to either the inboard or the outboard side of the propeller piston. The doubleacting governor also controls propeller feathering, unfeathering, reversing, and unreversing.

Referring to figure 13-1, the double-acting control consists of the following;

1. An engine-driven gear pump (2) which boosts the oil pressure from the engine to that required for the operation of the propeller pitch changing mechanism in the dome.



1. Electric head.
2. Booster pump.
3. High-pressure relief valve.
4. Shuttle valve.
5. Low-pressure relief valve.
6. Cutout switch.
7. Drive gear shaft.
8. Speeder spring.
9. Flyweight.
10. Solenoid valve.
11. Selector valve.
12. Auxiliary pressure check valve.
13. Pilot valve.

Figure 13-1.—Double-acting governor.

2. A pilot valve (13) which directs the booster pump oil through ports in the drive gear shaft to either the increase or the decrease pitch sides of the propeller piston.

3. The speeder spring (8) which, in opposition to the force exerted by the rotating flyweights (9), controls the position of the pilot valve and, in turn, is adjusted by the head assembly (1).

4. A relief valve system (3 and 5) that limits the load on the gear pump yet provides sufficient pressure to control the propeller under all normal operation conditions.

5. A solenoid valve (10) which directs the oil to position the pilot valve for reversing and unfeathering.

6. An auxiliary pressure check valve (12) for admitting auxiliary pump oil into the control.

7. A pressure cutout switch (6) that automatically terminates feathering.

CONSTANT SPEED OPERATION

On-speed Condition

During the on-speed condition, the centrifugal force of the flyweights is balanced by the force of the speeder spring. The pilot valve permits sufficient flow of oil to the outboard side of the propeller piston to compensate for internal leakage. The booster pump delivers oil under pressure to the region between the two metering lands of the pilot valve, to the high-pressure relief valve, and to the low pressure relief valve. The low-pressure relief valve maintains a 70-90 psi pressure differential across the pilot valve increase pitch metering land; i.e., between the booster pump oil and increase pitch oil. Thus, increase pitch oil pressure is maintained at a value sufficient to hold the blades at a constant angle. Oil which is bypassed by the relief valve returns directly to intake side of the booster pump.

Underspeed Condition

During the underspeed condition when the engine speed drops below the rpm for which the control is set, the force of the speeder spring exceeds the centrifugal force on the flyweights and moves the pilot valve downward. This action opens ports in the control drive gear shaft which connect the booster pump output to the decrease pitch or inboard side of the propeller piston, the oil flowing through the center of the propeller shaft and to the outer two holes of the oil transfer housing. It also goes to the servo piston valve through a passage along the outside of the oil transfer tube. The pressure, limited to 70-79 psi by the low-pressure relief valve, is not high enough to move the servo piston valve, but the piston moves outboard changing the blades to a lower angle. Return oil is forced back from the increase pitch or outboard side of the piston through

the oil transfer tube, the center port of the oil transfer housing, the propeller shaft, to the intake side of the booster pump through the hollow pilot valve. As the blades change to lower angle, the rpm increases, and the control returns to the on-speed condition. Propeller oil draining through the increase pitch passage is directed by the selector valve to back up the low pressure relief valve which opens when the pressure differential between propeller return oil and booster pump oil exceeds 70-90 psi.

Overspeed Condition

During the overspeed condition, the centrifugal force of the flyweights exceeds the force of the speeder spring and lifts the pilot valve. In this upward position, the pilot valve opens the ports in the drive gear shaft which connect the booster pump oil through the circle of holes inside the propeller shaft, the center of the oil transfer housing, and the oil transfer tube to the outboard side of the piston to increase the blade angle. This oil forces the piston inboard, turning the blades to a higher angle, thereby causing a reduction in rpm. The return oil is forced back from the inboard side of the piston through the outer ports in the transfer housing to the intake side of the booster pump. As the blades assume a higher angle, the engine rpm decreases and the control returns to the on-speed condition. Simultaneously with the above operation, the increase pitch passage from the drive gear shaft is connected through the selector valve to the spring side of the low-pressure relief valve to keep it closed. Since the propeller piston is moving, the oil pressure during overspeed will not reach the setting of the high-pressure relief valve which thus will remain closed.

GOVERNOR HEAD CONTROL

Briefly, the governor head assembly affects engine rpm changes by responding to engine speed change information initiated in the cockpit or synchronizer. The governor head accomplishes this by changing the tension of the speeder spring. The flyweights reacting to regain a force balance with the speeder spring moves the pilot valve conveying an off-speed condition to the propeller. A change in engine rpm, which accompanies propeller pitch change, causes a change in the flyweight force until the original force balance between the flyweights and speeder spring is reestablished. When the original balance is achieved, the pilot valve is back in its original position which stops the pitch changing action. Governor action then resumes constant speed operation at the new engine rpm.

The governor head assembly consists of a housing, a speeder rack which rides on the speeder spring and is connected by a gear train to a stepmotor, and high and low rpm stops. A balancing spring is located above the rack to position the rack in an intermediate position approximating cruising rpm in case of breakdown of the head control. The stepmotor is a 3-phase a-c motor with a permanent magnet rotor. The 3-phase a-c power required to run the stepmotor is converted from 27 volts d.c. by a commutator switch and a set of capacitors located in the synchronizer. The commutator switch is aptly named, for it reverses the direction of current.

The construction of the commutator switch is essentially three fingerlike spring contacts mounted between a positive plate and a negative plate. Attached at the contact end of each spring contact is a two-pronged fork made of an insulation material into which a cam shaft is fitted. The cam shaft consists of three lobes—one for each spring contact—mutually spaced 120° apart about the axis of the shaft. The cam shaft is mechanically geared to the shaft of a d-c shunt motor. Looking at the action of one spring contact as the cam shaft rotates shows that the contact follows a sequence of going positive, zero, negative, zero, positive, etc. The two remaining contacts follow the same sequence at succeeding 120° intervals of cam shaft rotation. The spring contacts are connected to corresponding phase windings of the stepmotor. Continuous rotation of the commutator switch cam shaft produces a 3-phase alternating current in the stepmotor windings.

The governor head can be controlled by one of three modes. They are as follows:

1. Manual control mode.
2. Synchronizer control mode.
3. Master lever control mode.

All these control modes are initiated in the cockpit by the pilot.

Manual Control Mode

As shown in figure 13-2, essentially three components are used in manually controlling

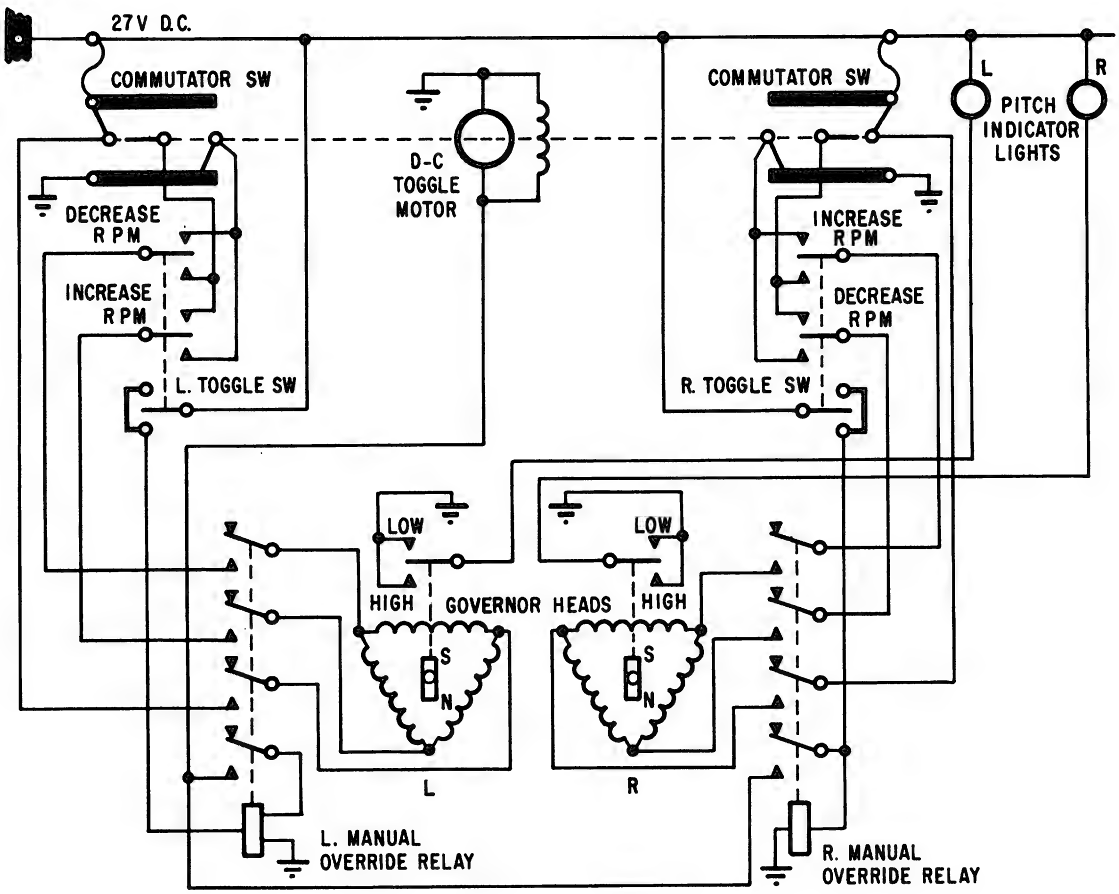


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Figure 13-2.—Governor head manual control schematic.

each governor head: (1) a three-pole, double-throw toggle switch for manual control, (2) a commutator switch assembly located in the synchronizer, and (3) a manual override relay, also located in the synchronizer.

Figure 13-2 is a simplified schematic diagram for manual control in a two-engine aircraft. Note that only one toggle motor is used to drive the commutator assemblies, which is energized by either toggle switch.

Placing the right toggle switch to INCREASE RPM energizes the right manual override relay which (1) connects the output of the right commutator switch to the right governor head stepmotor and (2) applies 27 volts d.c. to the toggle motor which drives the commutator switches. Energizing the manual override relays also isolates the governor head stepmotors from synchronizer control, which is not shown in figure 13-2. The stepmotor drives the speeder spring rack down compressing the speeder spring moving the flyweights closer together which, in turn, moves the pilot valve into the increase rpm position.

The operation is the same when the toggle switch is moved to DECREASE RPM except the toggle switch reverses the two heads of the commutator switch to the stepmotor head, thereby causing the head magnetic field to rotate in the opposite direction. This function of the toggle switch makes it possible to use a unidirectional motor for controlling more than one engine at the same time.

High and low limit switches in the governor head assembly complete the circuit to the pitch indicator lights in the cockpit when the speeder rack reaches the maximum or minimum rpm limits.

Synchronizer Control Mode

The synchronizer control mode makes use of the engine tachometer generators for sensing engine rpm differences between the master engine and slave engines. While in the synchronizer control mode, the master engine is used for the reference rpm and the slave engines are "slaved" to the master engine. This is accomplished by the following components in the synchronizer unit:

1. Differential motor assembly.
2. Synchronizer commutator switch.
3. Master engine switching relay.
4. Manual override relay.
5. Synchronizer limiter.

The differential motor assembly includes two synchronous motors and a differential gear train. Each synchronous motor has a 3-phase stator and a permanent magnet rotor. The front (shaft end) synchronous motor of each of the differential motor assembles is connected to the master engine tachometer generator and the rear is connected to one of the slave engine tachometer generators. The engine rpm of the master and the slaves are transmitted from the tachometer generators to the synchronous differential motors as voltage frequencies to the stators of the front and rear motors of each differential motor assembly. This causes the front and rear rotors to turn at rates dependent upon the frequencies induced. Any difference in frequency causes the differential gear train, hence the output shaft, to rotate at a speed proprotional to the frequency difference and in the direction of the difference. A friction clutch is attached to the shaft of the motor to permit free rotation of the motor after stop gear has reached its limit, stopping further rotation of the commutator switch. The stop gear is slotted to permit rotation of the commutator switch to provide adjustment of the stepmotor heads within a range of ±3 percent of the master head setting. This limited range of synchronization is provided to prevent the slave engines from following a malfunctioning master engine to either rpm limit, takeoff or minimum. The latch assembly consists of an electromagnet operated pawl which locks the stop gear in position. When the latch is energized, the pawl is lifted from the stop disk to allow the disk to be repositioned by the centering spring. Since one end of the spring is attached to the stop gear hub and the other to the stop pin in the stop disk, the spring positions the stop disk so that the pin is in the center of the stop gear slot. The commutator switch assembly is the same as described under manual control mode.

Figure 13-3 shows a simplified schematic diagram of the synchronizer control mode.

The synchronizing control mode is usually used after the engines have been manually synchronized by the manual control mode. The pilot must first close the master lever and synchronizer control switch in the cockpit. This allows the engine tachometer generators and the differential motors to be connected to each other; it also connects the synchronizer commutator switch to the slaved engine governor head.

Manual control mode will override the synchronizer control mode when the pilot energizes the toggle switch. (See fig. 13-4.)

Master Lever Control Mode

By master lever control all engines are controlled simultaneously through the adjustment of the control shaft on the synchronizer box which is actuated through a cable or linkage system by the pilot's master rpm control lever. Essentially, the master control consists of a reversible d-c shunt motor which is mechanically connected to a commutator switch and then through a clutch to an off-seeking followup switch. (Note that the commutator switches in figure 13-4, although illustrated differently, are physically the same as those described and illustrated previously.) Movement of the master lever towards increase or decrease rpm energizes the field of the master motor in the direction to drive the followup element so that the mechanism will resume the OFF position. At the same time the commutator switch driven by the master motor energizes all control head stepmotors to adjust the speed settings in the direction of and proportional to the master element movement. Synchronizing is cut out during master lever control mode until the followup mechanism moves to the OFF position, except when the master lever is in calibrate (takeoff) position. Whenever the master control is advanced to the calibrate position, all controls are set to their positive high rpm stops, and the synchronizing feature is cut out so that failure of the master engine on takeoff will have no effect upon the slave engines.

In the event that it is not desired to draw takeoff power from one or more engines, it is possible to reduce power manually by using

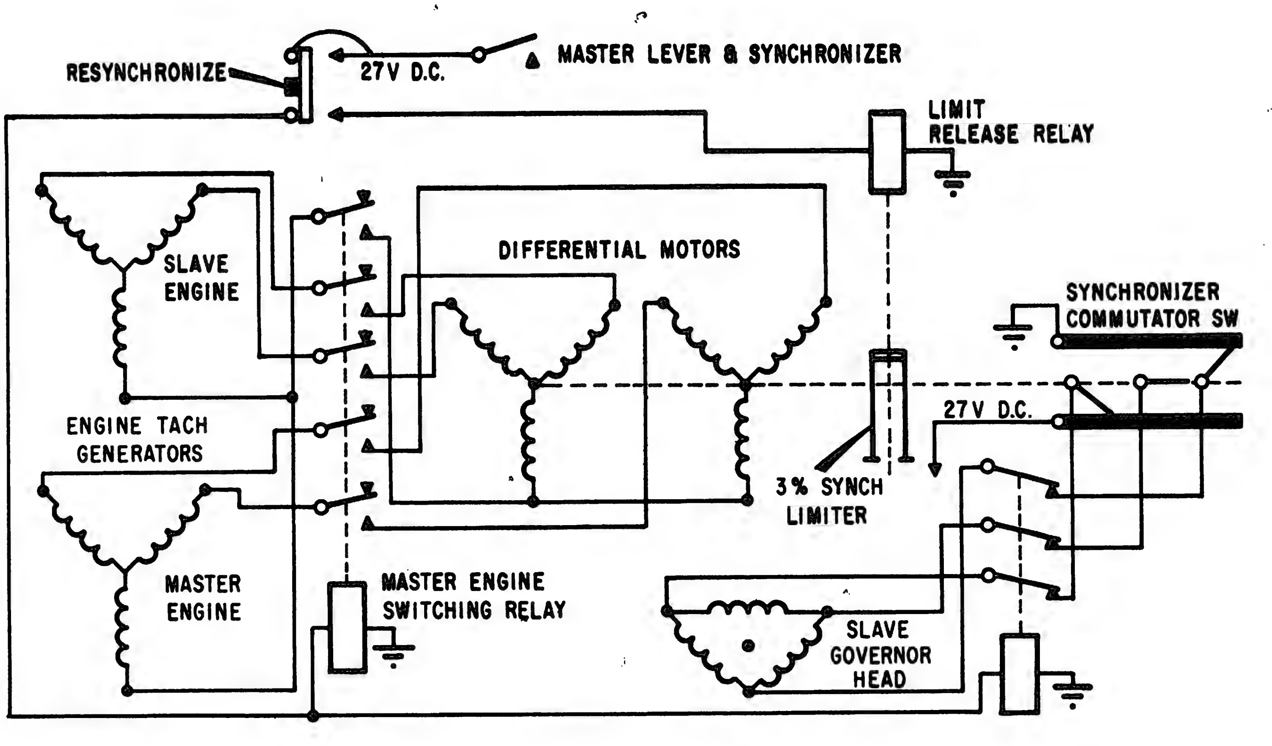

Figure 13-3.—Synchronizer control mode.

manual control mode to toggle one or more engines downward after, and only after, all engines have reached their high rpm stops. After takeoff, movement of the master lever to reduce rpm will produce equal rotation of all stepmotors so that if the controls were within the synchronizing range at the full high rpm position, they will remain within the range and automatic synchronizing will result. If any control had been reduced from its high rpm position at takeoff, its rpm would be reduced by a proportional amount (less 3 percent "spring-back") so that it will be set for a lower rpm than the rest of the engines.

Fire 13-4 shows a complete schematic diagram of the propeller synchronizer system. This system utilizes the three modes of operation that have been described. When studying these circuits refer to the written material. The preceding material in this chapter explained the operation of a two-engine synchronizing system. A four-engine synchronizing system is much the same as the two-engine system, except for the duplication of toggle switches, manual override relays, takeoff relays, toggle motor commutator switches, and differential motors.

DOUBLE-ACTING GOVERNOR CONTROL

Feathering

The feathering circuit (fig. 13-5) contains a pushbutton feathering switch, a pressure cutout switch, a blade switch, two relays, and an auxiliary (feathering) pump.

The feathering operation is started by depressing the feathering switch pushbutton. This completes the switch holding coil circuit through the pressure cutout switch to ground, the circuit to the feathering pump relay L7, and the circuit through relay L2 to ground at the No. 3 blade switch. The feathering motor relay completes the connection to the feathering motor for operating the feathering pump. When relay L2 is energized during feathering, an alternate ground for the holding coil is supplied in case a pressure surge should open the cutout switch prematurely.

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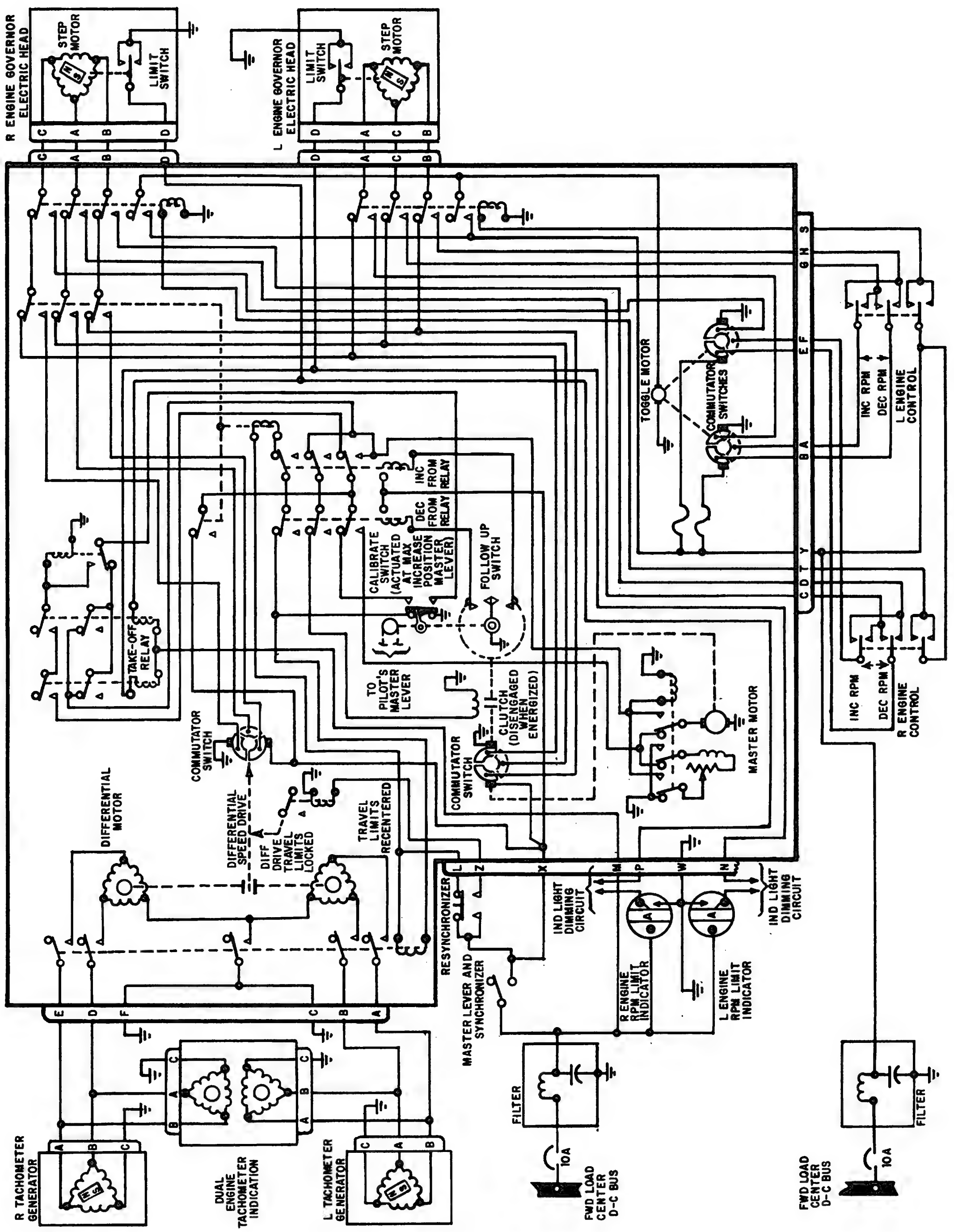

Figure 13-4.—Propeller synchronizer schematic diagram.

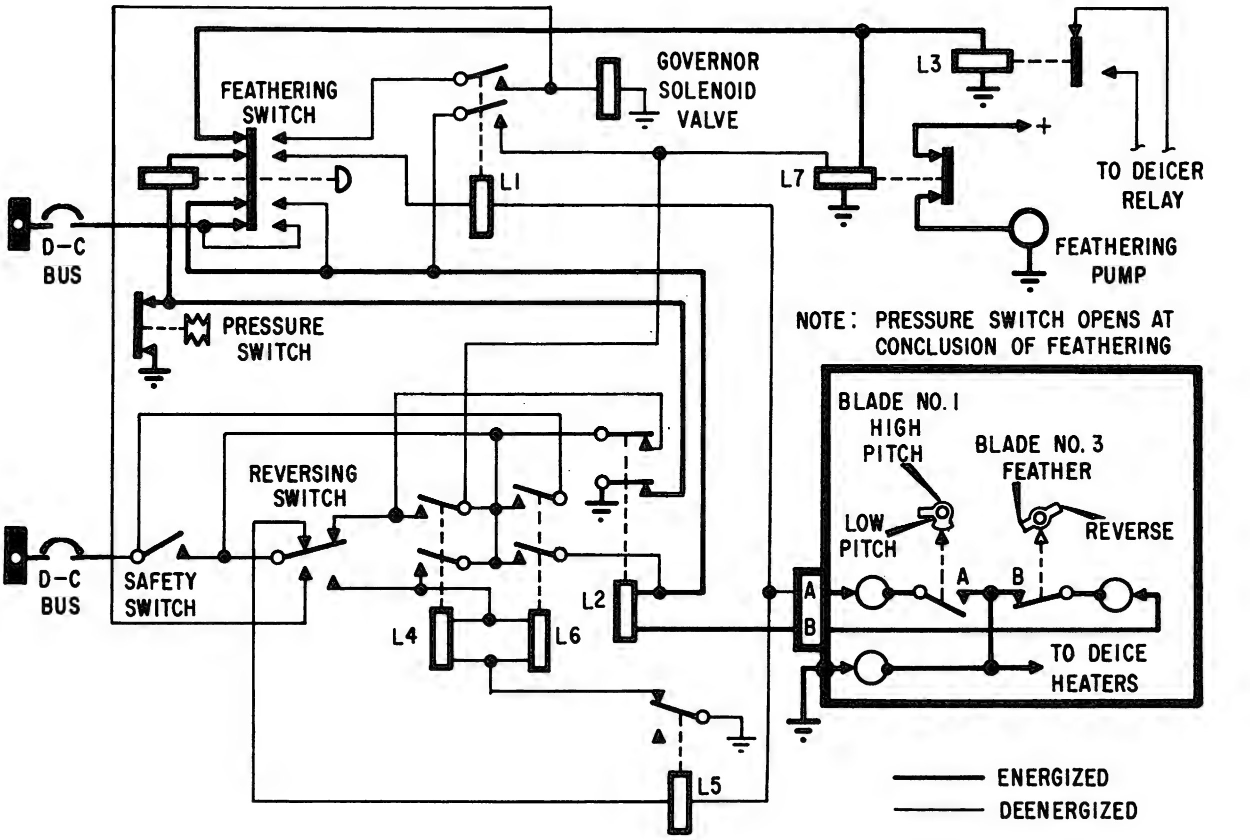

Figure 13-5.—Feathering circuit schematic diagram.

Auxiliary (feathering) oil enters the governor control through the auxiliary pressure check valve. It also flows into the lower pilot valve positioning chamber raising the pilot valve to the increase pitch position. As soon as the pilot valve is shifted, oil passes through the selector valve and backs up the low-pressure relief valve. With the same pressure on both sides of the valve, it remains closed. The oil continues through the increase pitch passages in the control to the propeller through the oil transfer housing and the oil transfer tube to the outboard side of the propeller piston. As the piston is forced inboard, the rotating cam turns the blades to the feathered angle. Just beyond the feathering angle, No. 3 blade switch contacts the feathering signal cam lobe and breaks the ground circuit from relay L2 to disconnect the alternate ground from the pushbutton holding coil. This permits the pressure cutout switch to terminate the feathering operation when the increase pitch oil pressure reaches the setting of the cutout switch. The propeller oil on the inboard side of the piston is forced back through the oil transfer housing and the propeller shaft to the intake side of the governor control booster pump to be recirculated as long as the control is operating.

Unfeathering

To unfeather, the feathering pushbutton is held out manually. Relay L1 is energized, through the No. 1 blade switch, completing the circuit to the feathering pump relay L7 to operate the feathering pump and to the solenoid valve in the governor control for directing oil pressure to position the pilot valve in a decrease pitch position. The feathering pump and the governor control booster pump supply the oil to both pilot valve positioning chambers to shift the pilot valve. The oil then flows

through the decrease pitch passages in the control to the propeller. At the same time it flows through the selector valve to back up the low-pressure relief valve.

In the propeller, the oil flows through the oil transfer housing to the inboard side of the propeller piston. The oil passes around the outside of the oil transfer tube to the servo piston valve but, since only a momentary surge of auxiliary oil is used, the servo piston valve will not stay open. The propeller piston is forced forward turning the blades toward low pitch. The oil in the outboard side of the piston is forced back through the propeller and propeller shaft to the intake side of the booster pump. Unfeathering action is terminated at any time by releasing the switch pushbutton. If the button is held out too long, the auxiliary (feathering) motor and pump will shut off automatically several degrees above the low blade angle when the No. 1 blade switch contacts the unfeathering (small) lobe of the control cam. This breaks the ground circuit from relay L1 to deenergize it. Opening relay L1 breaks the circuit to the feathering pump motor and the circuit to the solenoid valve in the governor control. The propeller now returns to constant speed control.

Reversing

Propeller reversing is initiated by moving the throttle into the reverse range. In order to move the throttle into the reverse range, the weight of the aircraft must be placed on the landing gear. This actuates a landing gear (safety) switch which energizes a throttle lock solenoid and removes the throttle detent to allow the throttle to be moved into the reverse range.

Figure 13-6 is the schematic diagram of a propeller reversing system. As each throttle lever is moved aft of the idle position, the safety and reversing switches are closed. This energizes the solenoid valve in the propeller governor, the feathering pump control relay L2, the feathering pump power relay L7, and relay L3 in the propeller deicer circuit. The ground for the circuit through the relay coil of relay L2 is completed at the blade switch on the No. 3 blade. This circuit is broken 5° prior to reaching full reverse position, interrupting the current through the feathering pump control relay L2, thus deenergizing L7 and L3. Relays L4 and L6 and the solenoid valve in the propeller governor remain energized as long as the throttle lever is in the reverse range.

Unreversing

When the throttle lever is moved from the reverse range forward to idle, the reversing switch returns to its normal position. This completes a circuit through the feathering pump control relay L2, power relay L7, propeller deicer relay L3, and interrupts the circuit to the solenoid in the propeller governor. The feathering pump then supplies oil to return the propeller blades to their normal position.

When the blades reach a position a few degrees above the low-blade angle setting of the propeller, the blade switch completes a circuit through relay L5, deenergizing the entire circuit (relays L2, L4, and L6), stopping the auxiliary pump by deenergizing relay L7, and returning control of the propeller to the propeller governor.

PREFLIGHT INSPECTION

The preflight inspection must be performed prior to the first flight of each day. It consists of a careful physical examination and an operational test of the electrical components of the aircraft. A preflight inspection for the propeller control system consists of a series of operational tests of the various components. These tests are discussed below.

Governor Action

It is recommended that the synchronizer switch be placed in the manual position during all ground checks other than when checking synchronizer operation. This prevents unnecessary running of the differential motors.

Upon completion of the engine warmup period, move the pitch control governing lever through its complete range from maximum to minimum rpm several times. Return each propeller to its normal position by means of its individual toggle switch. Due to propeller pitch change, the engine rpm should change accordingly. This change in rpm is indicated on the engine tachometer indicator.

This test serves to expel any air which may be trapped in the propeller system; and also it will enable you to detect improper operation of the propeller, the control system, or the engine.

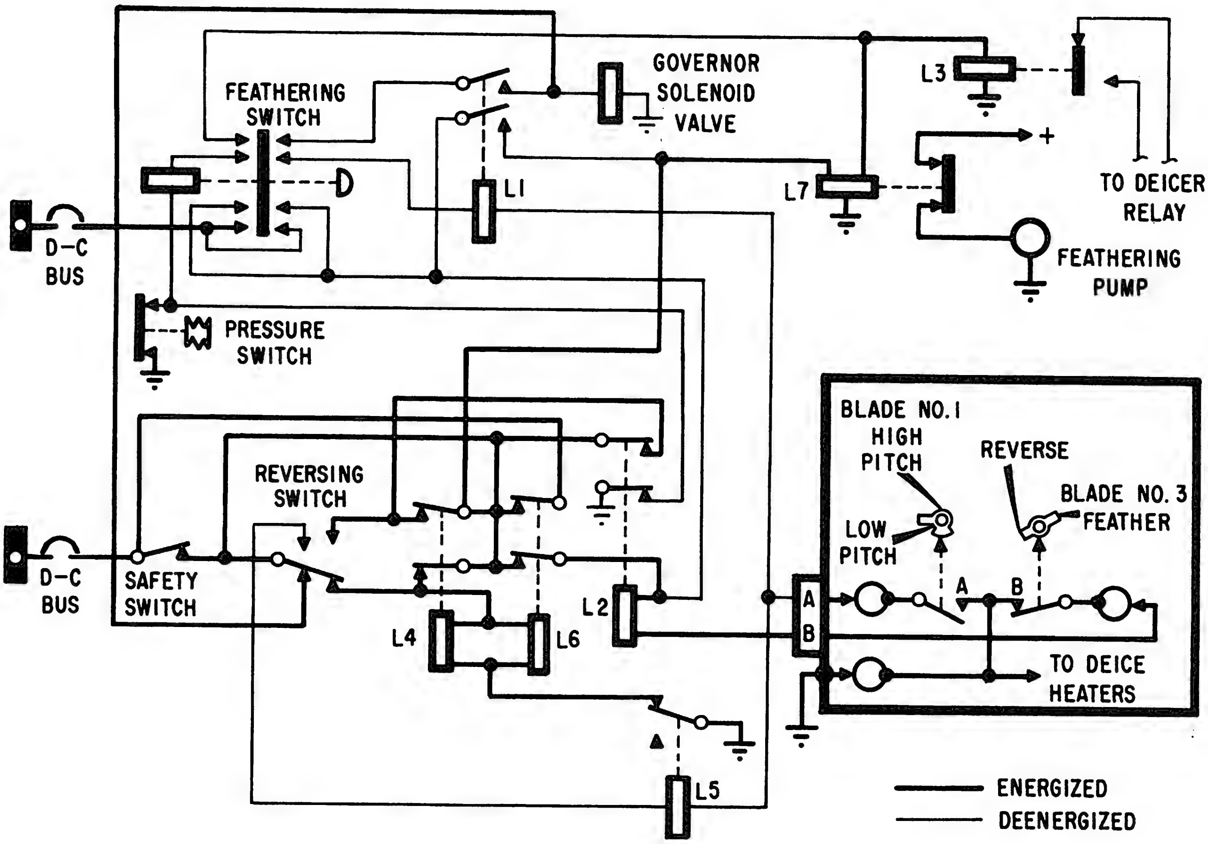

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Figure 13-6.—Propeller reversing schematic diagram.

Feathering and Unfeathering

The following method of testing the feathering operation with the engine running has two important advantages not attainable when carried out with the engine not running. They are (1) the main control pump aids the auxiliary pump in supplying the necessary oil pressure; and (2) the feathering test more closely approaches the conditions under which the propeller would be feathered in flight.

With the rpm control switch in the maximum rpm position and the engine operating at 1,500 rpm, depress the feathering switch and observe the ammeter for current drawn and the tachometer for rpm drop. When the engine speed has dropped to 1,000 rpm, pull out the pushbutton switch to its neutral position. The engine should return to 1,500 rpm. This test indicates that the feathering pump is operative. An unfeathering test on the ground is generally not required since the feathering test shows that the main parts of the system are operative.

Reversing and Unreversing

The propeller should not be run in the reverse position for extended periods, since the reverse direction of propeller airflow will cause excessive engine heating. Maintain a careful check on engine operating temperature during all reverse pitch operations. Before starting the test for reversing operations, be certain that the aircraft is secured from moving either forward or backward. On aircraft with tricycle landing gear, operation in the reverse position may cause the tail to drop and preventive measures should be taken.

Place the throttle lever in the idle position and the rpm control switch in the maximum rpm position. This places the propeller in the low-pitch position. Pull the throttle lever through

the detent into the reverse portion of the quadrant. The reversing solenoid is then energized by a throttle-actuated microswitch. This causes the propeller to operate beyond the normal low-pitch limit into the reverse pitch position. A slight increase in rpm is normal and should be expected. The amount of reverse thrust may be increased by moving the throttle lever farther to the rear and decreased by moving it forward toward the detent. To unreverse the propeller, advance the throttle lever past the detent to its original position. This unreverses the propeller, and the blades will rotate until they assume an angle of 5° to 12° above the lowpitch blade angle setting.

AIRCRAFT PROPELLER SYNCHROPHASING

The synchrophasing system discussed in this chapter is common to the P-3 and C-130 aircraft, which use T56 turboprop engines. The synchrophaser is a better quality synchronizer and governor control system than the one already discussed—a requirement demanded by turboprop engines.

Although the principles of operation of the mechanical governor and hydromatic propeller used on turboprop engines have many design improvements, they are similar enough to those already discussed and a further discussion is felt unnecessary for understanding the principles of operation of the synchrophaser.

The synchrophaser has different functions, depending upon the mode of governing selected by the pilot. In a mechanical governing mode, the synchrophaser does not function and the mechanical governor controls blade pitch, and hence propeller rpm during flight. In a normal governing mode, the synchrophaser supplements the mechanical governor by limiting engine transient speed changes from rapid power lever movement or to changes in flight conditions affecting propeller speed. In a synchrophasing governing mode, the synchrophaser supplements the mechanical governor by maintaining all propellers at the same rpm and, furthermore, by maintaining a preset phase relationship between the No. 1 blade of the master propeller and the No. 1 blades of each of the slave propellers. This serves to reduce noise and vibration in the aircraft. In the synchrophasing mode, the synchrophaser also provides the limiting of transient speed changes as it does in normal governing.

DESCRIPTION OF MAJOR COMPONENTS

The synchrophaser system consists of four main units: (1) the pulse generator, (2) the phase and trim control, (3) the speed bias servo assembly, and (4) the synchrophaser. (See fig. 13-7.)

Pulse Generators

The pulse generator provides the information needed by the synchrophaser system to produce speed and phase control of the aircraft propellers. Each propeller has a pulse generator which consists of a permanent magnet mounted on the propeller spinner and a stationary coil mounted in the governor control in close proximity to the rotating permanent magnet. A pulse is generated each time the permanent magnet passes by the coil; in other words, one pulse is generated for each revolution of the propeller.

Phase and Trim Control

The phase and trim control functions as a means of setting the phase relationships between master and slave propellers and as a means of trimming the master engine.

The phase and trim control consists of seven potentiometers which receive a fixed d-c voltage from the synchrophaser. The wiper of the master trim potentiometer supplies a voltage through the master select switch to the synchrophaser to trim the speed of the master engine. The other six wipers are connected to relay contacts which separate the wipers into two groups of three per group corresponding to engines 1, 3, and 4 when engine 2 is master and engines 1, 2, 4 when engine 3 is master. These wipers supply bias voltages to the phase correction circuits of the synchrophaser to set propeller phase angles of other than 0°.

Speed Bias Servo Assembly

The speed bias servo assembly functions as a means of translating synchrophaser electrical signals into a mechanical bias on the speeder spring in the mechanical governor.

The synchrophaser supplies the electric motor with a reference voltage which is 90° out-of-phase with the aircraft 400-Hz source. The synchrophaser also supplies a control voltage

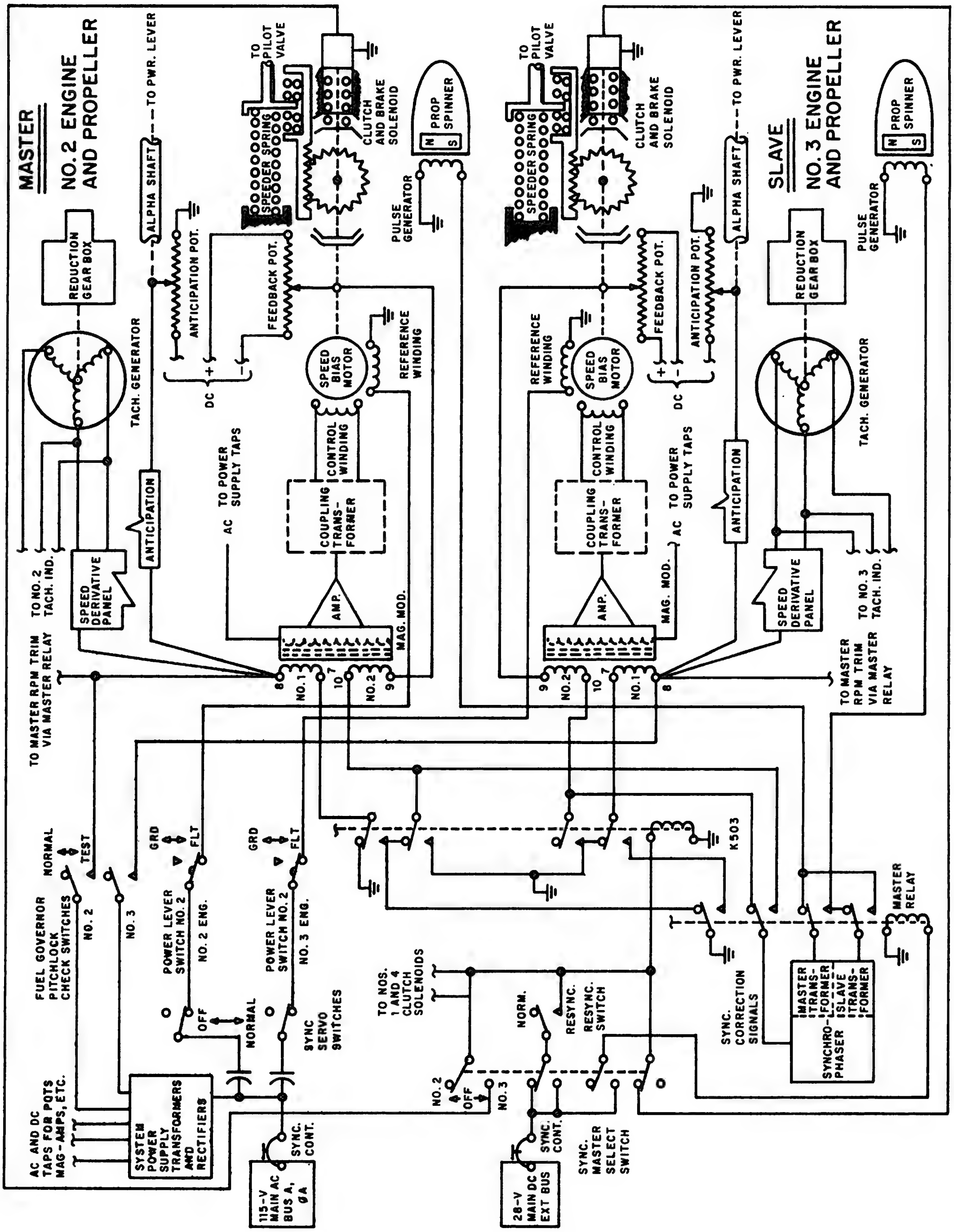

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Figure 13-7.—Synchrophaser control schematic diagram.

which will be either in-phase or 180° out-of-phase with the aircraft 400-Hz source. Hence, the in-phase control voltage lags the reference voltage by 90° and results in counterclockwise motor rotation when viewed from the output gear of the electric brake. The 180° out-of-phase control voltage leads the reference voltage and causes clockwise rotation. The amplitude of the control voltage determines motor speed and torque output.

The motor drives a reduction gear train which in turn drives a potentiometer wiper and the electric brake. The potentiometer receives a fixed d-c supply from the synchrophaser across its resistive element. When the motor rotates, the wiper transmits a corresponding feedback voltage to signal winding No. 2 of the magnetic modulator. The electric brake has a clutch controlled input and output shaft. The output shaft drives a lever which biases the speeder spring in the propeller governor. Energizing the clutch decouples the two shafts, locking the output shaft and leaving the input shaft free to turn.

The Synchrophaser

The synchrophaser has four channels which correspond to the aircraft's four engines. Each channel has a push-pull power amplifier which feeds the control winding of its corresponding servomotor in the speed bias servo assembly. The inputs to the push-pull amplifiers are furnished by magnetic modulators which use d-c control current to provide a phase and amplitude controlled a-c output to the amplifiers. Accordingly, all synchrophaser signal inputs are changed by the synchrophaser to d-c voltages proportional to the error before being applied to the modulator. The modulators are the signal summing devices for the two operational modes of the synchrophaser.

The magnetic modulators function on a core saturation basis. Each modulator consists of a d-c bias winding, a 400-Hz excitation winding, and two control windings (signal winding No. 1 and signal winding No.2). With no signals applied elsewhere, the 400-Hz excitation voltage appears as a 400-Hz output of negligible phase and amplitude due to the current in the bias winding. Any current in either or both signal windings will change the output. The magnitude of the current in the signal windings controls the amplitude of the output; the direction of the current controls the phase of the output. Thus, current from pin 10 to 9 in winding No. 2 and current from pin 8 to 7 in winding No. 1 of any modulator produces a 180° out-of-phase voltage with respect to the excitation voltage. Current in the opposite direction in the signal windings produces an in-phase voltage. Simultaneous currents flowing in opposite directions in the two signal windings produces a signal which is the algebraic sum of the two generated signals. The modulator thus produces a 400-Hz signal which is either in-phase or 180° out-of-phase with the excitation voltage. This signal is amplified and fed to the servomotor control winding. The 400-Hz voltage in the reference winding of the servomotor is applied through a series capacitor which gives the voltage a 90° phase shift with respect to the aircraft power source. Appropriate signals to the modulators can cause clockwise or counterclockwise rotation of the motor because of the phase difference in the motor windings. The use of the two signal windings in the modulators along with appropriate relay switching permits the two modes of operation of the synchrophaser—normal governing mode and synchrophasing mode.

OPERATIONAL MODES

The normal governing mode is used to provide improved engine response to transient rpm changes. In this mode, the synchrophaser receives signals from the power lever anticipation potentiometers and the engine tachometer generators. Signals from these items will result in a temporary resetting of the mechanical propeller governor to compensate for power lever changes and engine speed changes, and thus limit engine overspeeds or underspeeds.

The synchrophasing mode is used to synchronize engine speeds, to regulate propeller phase angles, and maintain the limiting features of normal governing mode. In the synchrophasing mode, one engine (2 or 3) is selected as the master. The master engine operates in normal governing mode while the other three engines (slaves) follow changes in speed or phase of the master within preset limits. (Figure 13-7 shows the synchrophaser control schematic diagram with engine No. 2 selected as master and engine No. 3 is slave. Slave engines 1 and 4, which operates the same as slave engine No. 3, are omitted for clarity.)

Normal Governing Mode

In normal governing mode, the propeller governor switch is in the NORMAL position and the power lever switch (not shown) is closed, thus providing reference voltages to the servomotors. The synchrophase master switch is OFF and the prop resynchrophase switch is in NORMAL. All relays are deenergized, resulting in the speed and phase error circuits being grounded. Each phase and speed error signal side of every magnetic modulator signal winding No. 2 (pin 10) is terminated on a dummy load (fig. 13-8) within the synchrophaser, while the other side (pin 9) is connected to the feedback circuit in the speed bias servo assembly. The controlling signals are to signal winding No. 1 (pin 8) of each modulator. All channels function identically while in the normal governing mode.

THROTTLE LEVER ANTICIPATION— Any power lever movement will cause a change in d-c voltage at the anticipation potentiometer wiper, which serves as a voltage divider for the RC circuit. The charging voltage for the capacitor is directly proportional to the position of the power lever. The change in charge on the capacitor is directly proportional to the rate at which the power lever is moved. If the power lever is moved to decrease engine power, the capacitor charges up to a more positive voltage value, resulting in a current from pin 7 to pin 8 in signal winding No. 2 of the magnetic modulator. A lagging voltage surge appears in the servomotor control winding, causing counterclockwise rotation which resets the mechanical governor towards decrease pitch to compensate for the reduced power setting. As the servomotor rotates, the feedback potentiometer begins cancelling the error signal by causing a current in signal winding No. 2 such that its magnetic field is in opposition to the magnetic field produced by the signal current in winding No. 1. This stops the servomotor. As the anticipator capacitor continues to charge to its new peak value, the current in signal winding No. 1 decays to zero. The feedback potentiometer, still applying voltage to signal winding No. 2, results in a leading voltage to the servomotor control winding and returns the motor to its original position, which corresponds to a zero volt feedback potentiometer position. Had the throttle lever been retarded very rapidly, the peak voltage would overcome the reverse bias on diode CR620 (fig. 13-8), which would limit the signal value to prevent overcompensation toward a flat blade pitch. For an increase in engine power, the capacitor discharges causing a current in the opposite direction in signal winding No. 1, which results in a temporary resetting toward increase pitch. The amount of reset in either case depends on the rate at which the lever is moved. Mechanical stops in the speed bias servo assembly limit speed resets to plus 10 and minus 10 percent regardless of the applied signal. Furthermore, stops in the propeller control valve housing linkage reduce the limits to plus 6 and minus 4 percent.

LIMITING ENGINE TRANSIENT SPEED CHANGES.—The speed derivative circuit in the synchrophaser (fig. 13-8) senses changes in engine rpm and produces output signals which dampen the engine rpm changes. The speed derivative circuit does this by translating the frequency changes received from one phase of the tachometer generator into signal voltages whose magnitudes vary at the rate the tachometer generator frequency changes. The signal voltage is fed to signal winding No. 1 of the magnetic modulator where it is summed and sent to the push-pull amplifier. It is then amplified and fed to the servomotor control winding. The servomotor adjusts the tension of the speeder spring which initiates a change in propeller pitch, thus dampens the change in engine rpm.

The action of the speed derivative circuit is further described as follows: The voltage produced on the collector of transistor Q603 is proportional to the output frequency of the tachometer generator. When engine rpm is constant the voltage on the collector is constant and capacitor C621 is charged through resistor R634 and signal winding No. 1 of the magnetic modulator. Current in signal winding No. 1 decays to zero as the charge on capacitor C621 reaches the potential on the collector of transistor Q603. When engine rpm changes, a change in the collector voltage of transistor Q603 proportional to the change in tachometer generator frequency causes capacitor C621 to change its charge at the rate in which the tachometer generator frequency is changing. This produces a current in signal winding No. 1 whose magnitude varies at the rate at which the engine is varying offspeed and whose direction is such that the amplified signal in the servo bias assembly control winding will drive the servomotor in a direction to dampen the drift in engine rpm.

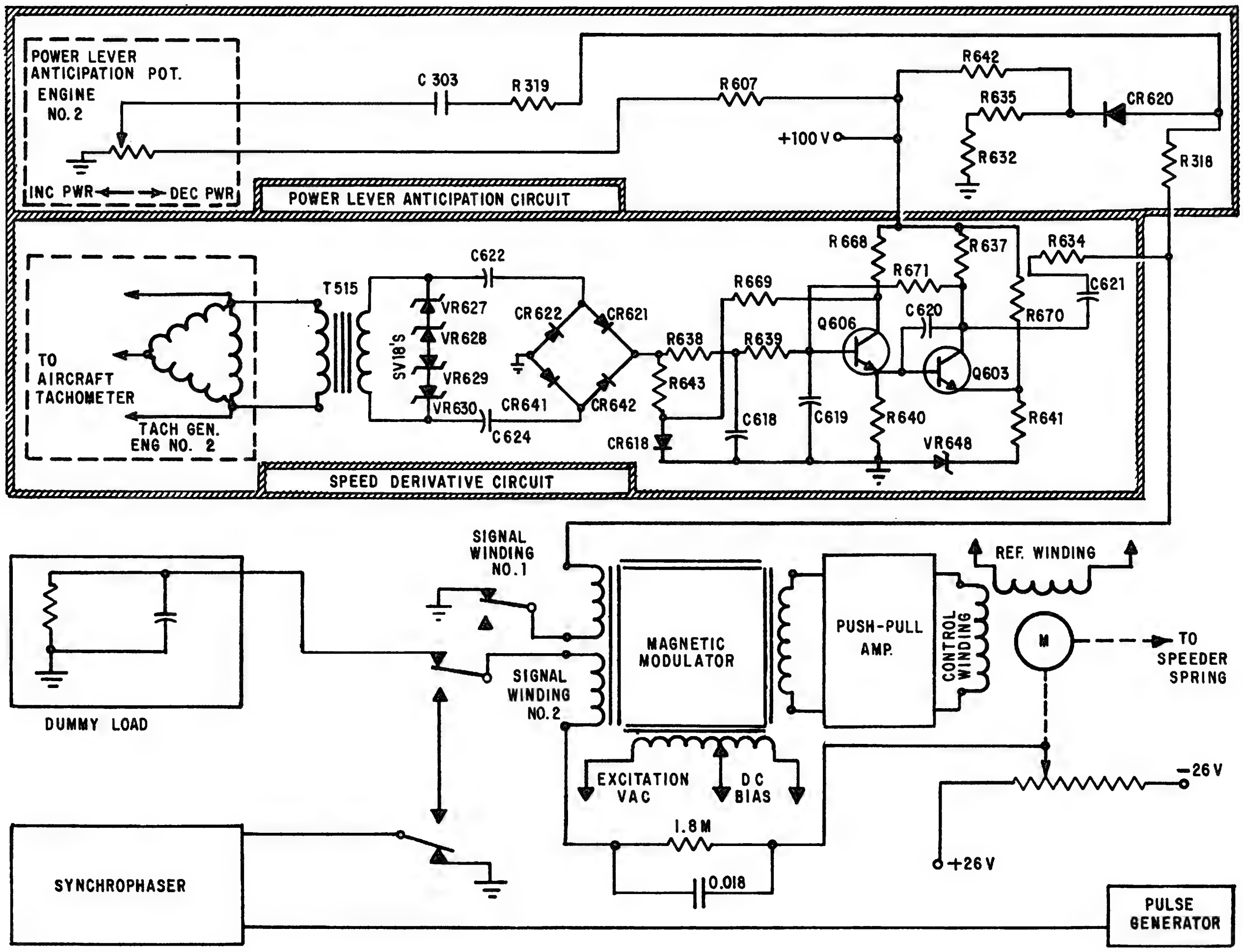

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Figure 13-8.—Power lever anticipation and speed derivative circuits in normal governing mode.

Speed error signals in signal winding No. 1 from the speed derivative circuit are canceled in the same manner as anticipation signals from the anticipation circuit are canceled.

The speed derivative and power lever anticipation circuits, being much more sensitive to engine rpm changes than the flyweight speeder spring force balance of the mechanical governor, supplements the governoring action of the flyweight and speeder spring, thereby improves the mechanical governor's response to changes in power lever settings and to changes in engine rpm.

Synchrophaser Mode

In adding synchrophasing to normal governoring mode, either ENG 2 or ENG 3 is selected by the synchrophase master switch (fig. 13-7). When the master engine is selected, relays are energized which remove the dummy loads from signal winding No. 2 of all magnetic modulators except the modulator of the master channel. Also, the outputs of the speed error and phase error circuits of each synchrophaser channel (except the master) are removed from ground and connected to signal winding No. 2 of their respective modulators. While the slave engines

are in synchrophasing mode, the master engine remains in normal governoring mode only. Essentially, pulses from the master engine are formed into sawtooth waves and then compared with the pulses from each of the slave engines in the respective slave channel sampling circuits. If slave pulses are not in phase with the master pulse (sawtooth), the errors are detected in the respective synchrophaser channel and fed to signal winding No. 2 of the channel magnetic modulator where they are summed with an error signals that may exist in signal winding No. 1. The resultant of the error signals is amplified and fed to the control winding of the respective speed bias servomotor which alters the tension of the slave governor speeder spring, thus correcting for engine speed differences and propeller blade angle errors. (One channel of the synchrophasing circuit is shown in figure 13-9.)

Phase and speed error sensing is described in the following paragraphs.

SAWTOOTH FORMER.—The pulse from the master pulse generator is transformer coupled to the sawtooth former, whereas the slave pulse generators are transformer coupled to the channel sampler circuits. Figure 13-10 (A) and (B) illustrates the master pulse and the resultant sawtooth formed in the sawtooth former.

SAMPLING CIRCUITS.—The pulses from the three slave engines are coupled to the grids of the sampling circuit tubes, while the sawtooth voltage is applied to the plate of one tube and the cathode of the other tube in all sampling circuits. The positive going portion of the slave pulse places the tubes in a conductive state. (Since sampling is the same in all channels, only one channel is discussed.) Referring to figure 13-9, if the sawtooth is at zero potential at the time that the slave pulse occurs, neither tube conducts and no signal is applied to the phase difference and speed error circuits. If the sawtooth is in the positive region at this time, tube V205 conducts. The corresponding voltage changes are applied to the grid of the phase difference tube V206A. The nature of the sampling action can be seen by referring to figure 13-10. The time interval between master pulses is the time interval for 360° of propeller rotation as shown in figure 13-10 (A). The time interval to the sawtooth which is generated by the master pulse is 360° as shown in (B). The half-time interval, or 180° position, is the sawtooth zero potential point as shown in (C). When the slave pulse occurs at the zero point, the propellers are on-phase and there is a 180° phase difference between them. All references to slave pulses are given with respect to the 360° interval and the point of occurrence of the slave pulse determines the magnitude of signal developed in the sampler circuit as shown in (D). This signal represents the phase difference between propellers.

NOTE: Since the propellers are four bladed, the relative blade position between the master and slave propellers is exactly the same when the slave propellers differ from the master by one-half revolution. Therefore, a 180° phase difference is considered as an on-phase condition in pulse comparisons.

PHASE DIFFERENCE CIRCUITS.—The phase difference circuits receive the voltages generated in the sampling circuit at the grids of the respective tubes. With a 180° phase difference signal at the grid of V206A (fig. 13-9, the voltage at the wiper of potentiometer RP251 is adjusted to null or zero volts. This voltage changes proportionally with the grid signal from the sampling circuit, and hence represents the phase difference between propellers. The effect of this voltage on synchrophaser output is discussed subsequently.

OFF-SPEED CIRCUITS.—When the propeller goes offspeed, the sampling circuit senses the condition as a sharp voltage change. (When the slave propeller is on-speed, the slave pulses occur at the same time interval in each successive sawtooth cycle.) When an underspeed or overspeed condition develops, the slave pulse occurs at a different position for each sawtooth cycle until, at one point, the slave pulse falls up or down the sawtooth (fig. 13-11). This can be thought of as a phase error which occurs too rapidly for the phase error circuit to compensate for. During an underspeed condition, the voltage applied to the phase difference tube suddenly changes from positive to negative. (See fig. 13-11 (A).) For an overspeed condition, the voltage suddenly changes from a negative to a positive.

The action of the off-speed circuit is described as follows: The underspeed voltage change registered in the plate circuit of the phase difference tube is coupled to the off-speed circuit by capacitors C253 and C254. (Refer to fig. 13-9.) The voltage change in the plate circuit is positive and the reverse bias on diode CR251 is reinforced, but the reverse bias on diode CR252 is momentarily overcome, allowing capacitor C255 to charge

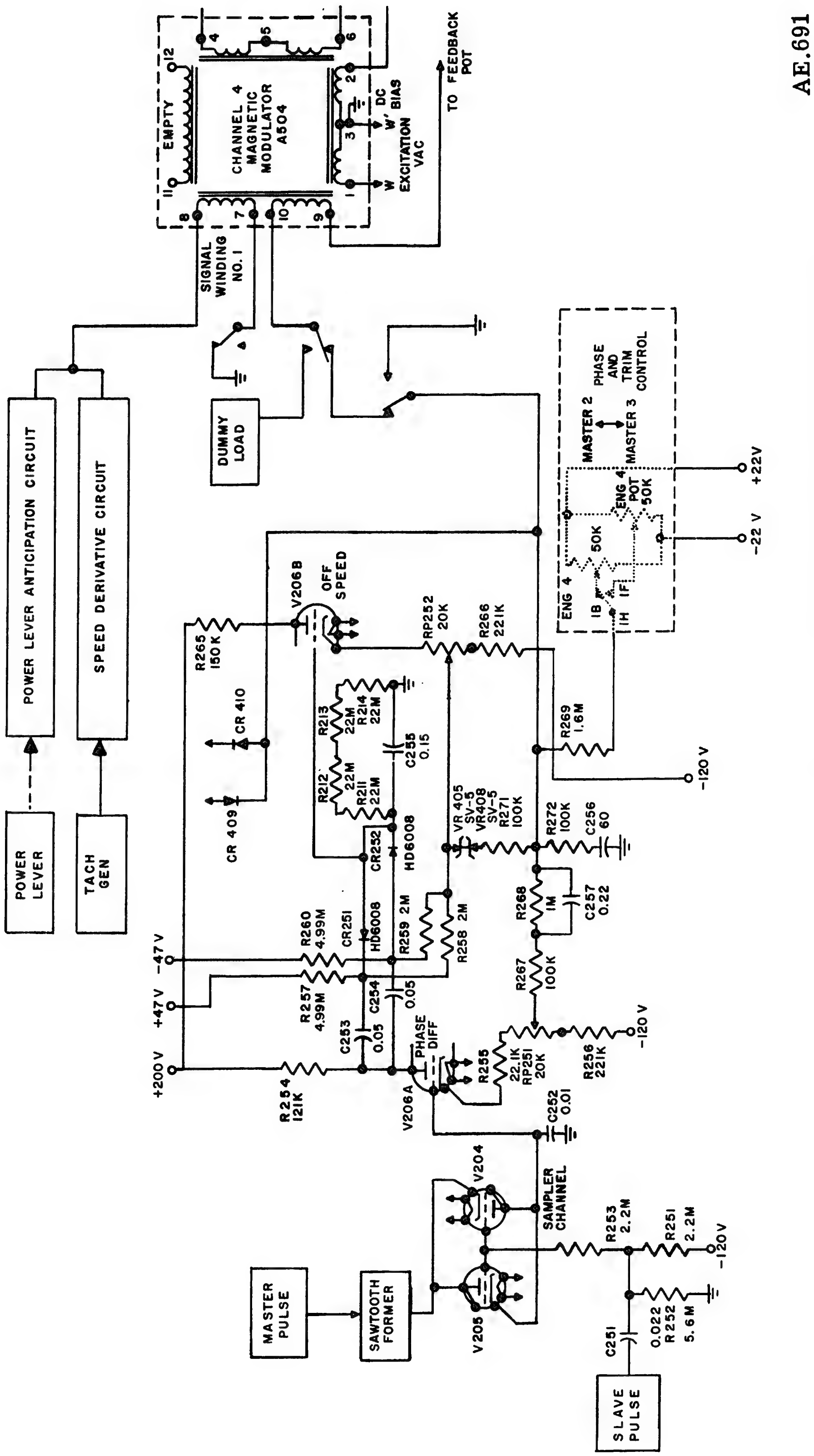

Figure 13-9.—Synchrophaser schematic diagram, synchrophaser mode (slave channel).

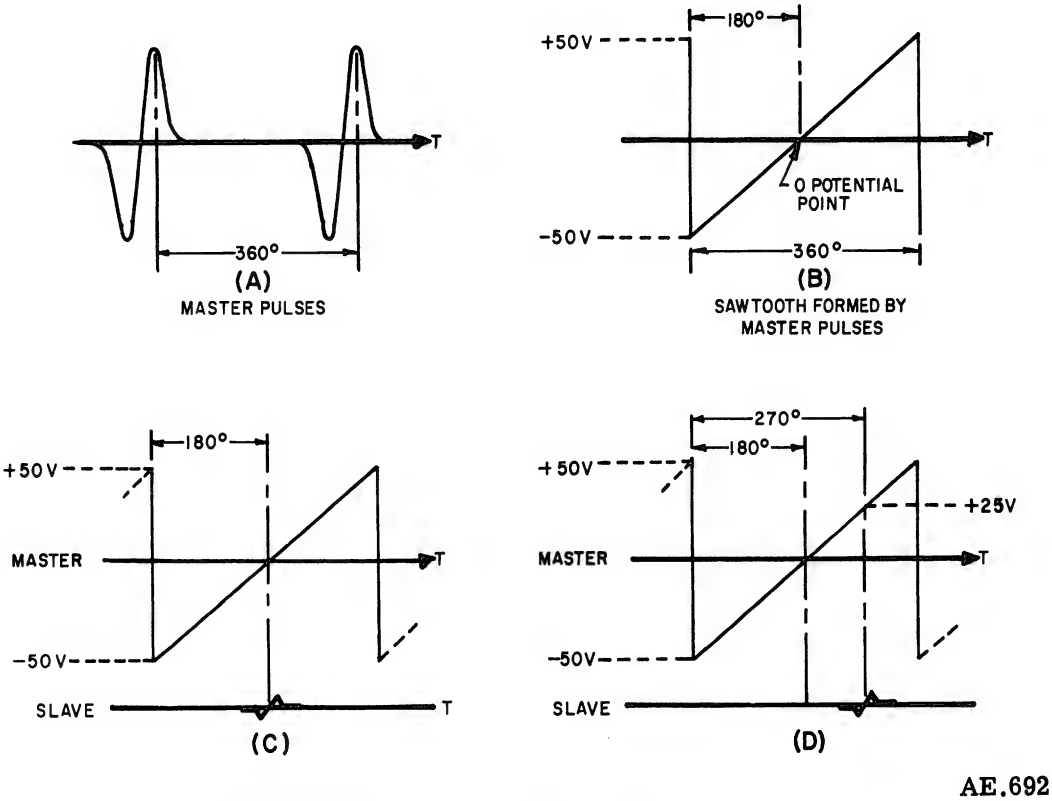

Figure 13-10.—Master and slave pulse comparisons.

positively. Capacitor C255 will discharge slowly through its parallel resistive network and maintain a grid bias on the off-speed tube V206B. (For an overspeed, diode CR251 conducts and charges capacitor C255 negatively.) Successive sharp voltage changes will add to the charge on capacitor C255 until the off-speed condition is corrected. Like the phase difference circuit, the off-speed circuit has a zero volt adjustment potentiometer in the cathode circuit. The pulsating voltage generated at the wiper by the changing grid bias on the tube is called speed error voltage. The effect of this voltage is discussed subsequently.

SIGNAL SUMMING.—As shown in figures 13-9 and 13-12, the phase difference and speed error voltages are coupled to the signal summing point. Also connected to this point, are the limiting circuit, the phase control potentiometer, and magnetic modulator signal winding No. 2. Any difference in potential between the signal summing point and the feedback potentiometer will cause a current in the modulator winding and will result in motor movement which, in turn, will cause the feedback poteniometer to null whatever potential is at the summing point.

Error Corrections and Two-Percent Limiting

PHASE-ERROR CORRECTION.—When the slave propellers are not on-phase, the phase difference voltage acting through the averaging circuit to the summing point causes speed bias servomotor rotation to correct the off-phase condition, provided the phase control potentiometer (fig. 13-12) is set for zero volts. In this case the phase difference voltage actually represents phase error. However, if it is desirable to have a slave propeller maintain a specific angle of lead or lag with the master propeller, then the phase control potentiometer is adjusted to cancel the phase difference voltage

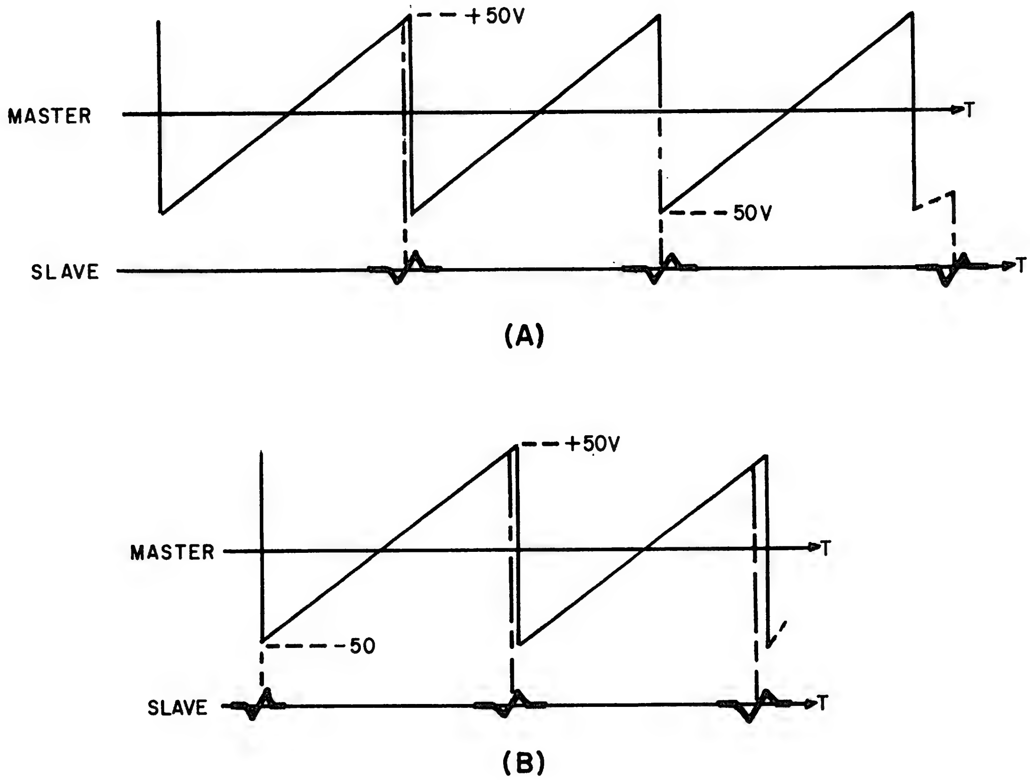

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Figure 13-11.—Off-speed pulse comparison. (A) Slave underspeed; (B) Slave overspeed.

at the summing point. For example, to maintain a slave lead of 10° from the 180° position of the master pulse, the phase control potentiometer is adjusted to cancel the phase difference voltage which is generated when the slave propeller leads the master propeller by 10°. Thus, when the slave propeller leads by 10°, the net potential at the summing point is zero and the speed bias servomotor will not move. When the slave propeller changes from the 10° lead condition, the phase difference voltage changes, and the net potential at the summing point is the difference between the phase control potentiometer setting and the phase difference voltage. This is how the phase error voltage and its magnitude depends on the slave propeller's degree of lead or lag from the 10° lead condition. The manual phase control is adjustable to allow a slave lead or lag of 45°.

SPEED ERROR CORRECTION.—During the phase error correction, Zener diodes VR405 and VR 408 isolate the speed error potentiometer RP252 from the signal summing point. When an off-speed occurs, these diodes conduct, connecting the speed error circuit to the summing point. For large speed errors, the speed error signal is a pulsating d.c. of very low frequency. At the same time, the phase error signal is a rapid d-c step voltage consisting of sharp potential changes which trigger the speed error circuit. The d-c step voltage changes developed in the cathode circuit of V206A are averaged and effectively blocked by resistor R268 and capacitor C251. The sharp potential changes passing resistor R268 and capacitor C251 are leaked to ground by resistor R272 and capacitor C256, leaving the speed error signal in control. When the engine reaches on-speed condition, but is still out-of-phase, the speed error signal drops off until a point is reached where the Zener diodes stop conducting and the phase error signal assumes control.

TWO-PERCENT LIMITING—The potential at the summing point is limited to plus or

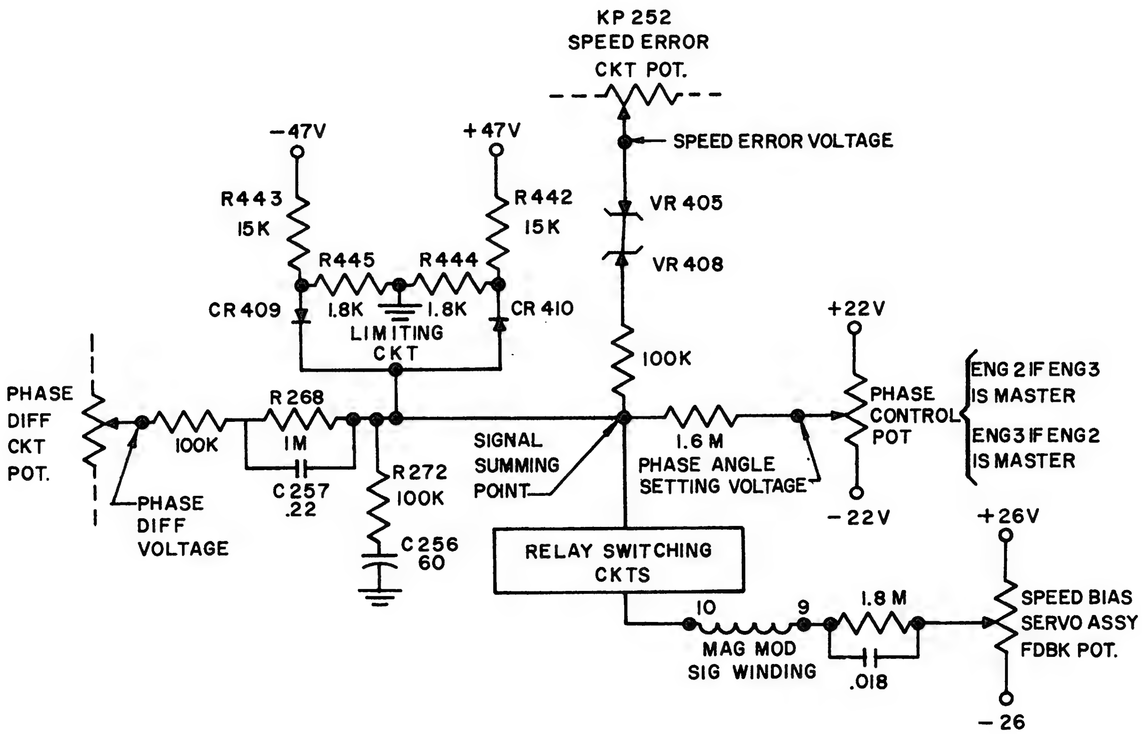

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Figure 13-12.—Simplified schematic of signal summing.

minus 5 volts by the limiting circuit (R442, R443, R444, R445, CR409, and CR410) which clips any signal outside of the range limit. In the case of the off-speed circuit, this limited signal will provide only enough amplified output to drive the speed bias servomotor to correct for a two-percent speed change. This occurs because the motor movement results in a feedback voltage which cancels the speed error signal. Thus, the slave propeller cannot follow large speed changes of the master engine, preventing a slave from following an overspeeding or underspeeding master.

Resynchrophasing

The need for resynchrophasing arises from the nature in which phase angle correction circuits operate. As phase errors occur, the servomotor rotates to correct the error. At the same time, the feedback potentiometer moves and cancels a portion of the error signal. As the phase error is corrected, the phase error signal decreases until it matches the feedback signal. When this occurs, the potential at the summing point is zero and the motor stops moving, leaving a portion of the error uncorrected. This is insignificant for errors which occur about a set point—leading and lagging errors. However, for errors that continually occur in one direction, the uncorrected error accumulates and it can become large enough to reduce the efficiency of the system. To overcome this, a procedure is provided, whereby the bias on the mechanical governor is locked while the servomotor recenters to a zero volt feedback position. This is called resynchrophasing.

The resynchrophasing operation is as follows: While in synchrophase mode, place the prop resynchrophase switch in the RESYNCH position. This energizes the electric clutch-brakes on the slave engine speed bias servo assemblies. The brakes lock the output shafts and the clutches decouple the input and output shafts, leaving the input shafts free to turn.

Locking the output shaft retains whatever mechanical bias is present on the mechanical governor. At the same time, relay K503 is energized, which opens the singal winding No. 1 circuits on the magnetic modulators. (The master channel remains in normal governing mode through a parallel ground provided by the master relay to signal winding No. 1 of the master channel modulator.) (See fig. 13-7.) An instant later (a time delay sufficient to assure brake and clutch actuation before allowing the recentering action), relays are deenergized, which remove the phase and speed error circuits from the slave channel magnetic modulators and connect the dummy loads. The only input to the slave channel magnetic modulators is now the feedback potentiometer acting into the dummy load through signal winding No. 2. A signal is then generated, driving the motors until the feedback voltage is zero. When the prop resynchrophase switch is released, all circuits return to synchrophasing mode. The accumulated phase error can now be corrected.

TROUBLESHOOTING HINTS

When a trouble occurs in the electrical controls of the propeller system, the first step of troubleshooting is to determine which part of the system is malfunctioning. This can be determined during the preflight check. The next step is to refer to the electrical schematic and the trouble shooting chart found in the Maintenance Instructions Manual for the aircraft, and then proceed to analyze the trouble.

Table 13-1 is a typical troubleshooting chart which illustrates a systematic approach for isolating faulty components or wiring in the synchrophaser system.

Table 13-1.—Synchrophaser system troubleshooting.

Trouble	Probable cause	Remedy
1. Steady overspeed or underspeed on one or more engines in synchrophasing mode.	Pulse generators.	a. If condition exists on a slave engine, check slave pulse input to synchrophaser. Adjust coil to magnet clearance replace parts, or correct aircraft wiring problem. b. If condition exists on all three slaved engines, check master pulse input to synchrophaser. Adjust coil to magnet clearance, replace parts, or correct aircraft wiring problem. c. If there is no problem with pulse inputs, replace the synchrophaser.
2. Steady overspeed or underspeed on one engine in normal governing.	Speed bias servo assembly feedback potentiometer.	a. Open circuit to feedback potentiometer on troublesome engine. Check for continuity from the synchrophaser connector to the potentiometer. Resistance into the feedback potentiometer should be approximately 7 to 10 kilohms.

Table 13-1.—Synchrophaser system troubleshooting—Continued.

Trouble	Probable cause	Remedy
2. Steady overspeed or underspeed on one engine in normal governing—Continued.		b. Wiring reversal in feedback potentiometer circuit. Remove propeller control valve housing cover. Check voltage polarity at potentiometer. Voltage at blue lead terminal should be positive with respect to ground. Voltage at the red/white lead terminal should be negative with respect to ground.
	Synchrophaser.	Replace synchrophaser.
	Resynchrophaser circuit.	Brake-clutch not being energized or not operative. Check for approximately +28 volts across red/yellow and gray (gnd) leads to brake-clutch. The voltage must be present on engine No. 2 when master No. 3 is selected, and on engine No. 3 when No. 2 is selected. The voltage must be present on engine No. 1 and No. 4 when either master is selected and the resynchrophase switch is actuated. If voltage is not present, check switches and aircraft wiring and repair or replace. If voltage is present, check to see if the brake lever is locked in position when voltage is applied and is released when voltage is removed. If not, replace propeller control valve housing.
3. Slave will not synchophase with one of the masters.	Pulse generator.	Check pulse input to synchrophaser from the troublesome master. Adjust coil to magnet clearance, replace parts, or correct aircraft wiring problems.
	Synchrophase master switch.	Check switch for correct wiring and transfer of circuits. Repair and replace.
	Synchrophaser.	Replace synchrophaser.
4. Slaves will not synchrophase with either master. (Does not follow master speed changes.)	Power source.	Check to see that synchrophaser is receiving 115-volt, 400-Hz operating voltage. If not, check aircraft wiring and circuit breakers. If voltage is present, check fuse on the front of the synchrophaser.
	Synchrophaser.	Replace synchrophaser.

Table 13-1.—Synchrophaser system troubleshooting—Continued.

Trouble	Probable cause	Remedy
5. One slave will not synchrophase (stays at one speed).	Speed bias servo, synchrophaser, propeller governor, or throttle lever switch.	The trouble must be isolated. Perform a fuel topping and pitch lock test on the affected engine. If engine overspeeds as normal for the test, the switches for the servomotor reference winding is good, the servo is good, and the synchrophaser amplifier is good. The servo feedback potentiometer circuit or the pulse generator may be causing trouble. Check pulse input from affected engine to synchrophaser. Check feedback potentiometer per trouble No. 2 in this table. If these check good and the fuel topping check is good, replace the synchrophaser. If fuel topping test is not normal, perform continuity checks on aircraft wiring and switches to the servomotor reference winding. If this is good, replace the synchrophaser and perform another fuel topping test. If response is not normal, check continuity to servo control winding. If good, replace the propeller control valve housing.
6. Master cannot be trimmed with phase and trim control.	Phase and trim control or synchrophaser.	Select other master. If this master can be trimmed, replace the synchrophaser. If both masters cannot be trimmed, replace phase and trim control. If replacement does not correct trouble, check aircraft wiring.
7. Overspeed or underspeed for throttle chop or burst. Response same as or worse than mechanical governing.	Throttle anticipation potentiometer or synchrophaser.	Remove propeller control valve housing cover. Observe that servomotor responds to throttle movements by driving the output lever. If no action is present, run a continuity check from the synchrophaser connector to the throttle anticipation potentiometer. Resistance across potentiometer should be approximately 250 kilohms. Check wiper to ground resistance using a 2-kilohm resistor in series with the meter. Set the throttle at full reverse. Resistance should be approximately 252 kilohms. Slowly advance the throttle to takeoff. Resistance should decrease smoothly to a value of approximately 2 kilohms. Slowly retard throttle to reverse. Resistance should follow by increasing smoothly to approximately 252 kilohms. If open is found,

Table 13-1.—Synchrophaser system troubleshooting—Continued.

Trouble	Probable cause	Remedy
		check aircraft wiring. If good, replace propeller control valve housing. If resistance change is not smooth and continuous, replace valve housing. If no problem can be found, replace the synchrophaser.
8. No speed stabilization. Cycles required to settle at governing rpm are the same as in mechanical governing after a speed change.	Tachometer generator or synchrophaser.	Check for tachometer generator voltage at synchrophaser connector with propeller at 100 percent rpm. Voltage should be approximately 16- to 23 volts rms. If no voltage or out of limit voltage, check aircraft wiring or replace tachometer generator. If voltage is present, replace synchrophaser.
9. Erratic governing in synchrophasing mode or in normal governing.	Intermittent open or short in circuits.	a. This type of trouble must be found by carefully checking for loose contacts on all accessible connectors and components of the system. Poor connections are a likely cause of the trouble. b. Other possible causes are in intermittent throttle anticipation potentiometer, servo feedback potentiometer or phase and trim control potentiometer. c. When erratic governing is noted on all engines, it is possible that voltage transients in the 115-volt, 400-Hz supply to the synchrophaser are causing the trouble. Check supply voltage.
10. Small steady-state changes of 1/2 to 2 percent in engine speed in synchrophasing or normal governing.	Phase and trim control.	a. If changes occur in synchrophasing on all engines, phase and trim control or wiring between phase and trim control and synchrophaser may be the problem. Check wiring. If wiring is good, replace phase and trim control or the synchrophaser. b. If changes occur in synchrophasing on one engine, check pulse to synchrophaser for affected engine.

Table 13-1.—Synchrophaser system troubleshooting—Continued.

Trouble	Probable cause	Remedy
10. Small steady-state changes of 1/2 to 2 percent in engine speed in synchrophasing or normal governing—Continued.	Synchrophaser.	If changes occur in synchrophasing or normal governing on all engines regardless of selected master, replace synchrophaser.
	Speed bias servo assembly.	If changes occur in synchrophasing or normal governing on one engine, servo assembly clutch may be slipping. This can be determined by performing a fuel topping and pitch lock test. A shift in governing rpm after the test is completed indicates a slipping clutch. Replace the propeller control valve housing if this is the case.
11. Oscillations in engine speed in synchrophasing or normal governing.	Pulse generator.	If oscillations occur on all engines and only with one master, check the pulse from that particular master. Adjust coil to magnet gap or replace parts.
	Tach generator.	If oscillation occurs on one engine when in synchrophasing or normal governing, check tachometer generator. Excessive wear or play in the shaft or rough bearings can cause a variable frequency input which the synchrophaser interprets as change in engine speed. Replace the tachometer generator if any of the foregoing conditions exist.

CHAPTER 14
TEST EQUIPMENT

In previous chapters of this manual, certain maintenance practices, equipment, systems, and procedures have been discussed. The current chapter is devoted to a discussion of some of the equipment used by the electrician in the maintenance of electrical equipment. Also included in this chapter is a brief discussion of the principles involved in the performance of certain tests.

All test equipment is designed and constructed to perform tests of one or more specific types. These tests are used to determine the quality of operation and alinement of systems, sets, components, or parts. The performance characteristics of units in aircraft are determined, to a large measure, by the quality and accuracy of the test equipment and the skill and care with which the electrician uses it. The purpose of this chapter is to acquaint the AE with some of the major classes of test equipment, their use, and their proper treatment. All test equipments discussed in this chapter are in common fleet usage at the time of writing.

The equipments discussed in this chapter are also commonly used in shore establishments. The selection of specific equipment for discussion is based primarily on the basis of functional types and applications. The discussion devoted to each individual item is necessarily brief, and is not intended to provide complete operational or maintenance procedures. Neither is it intended to supply detailed theory of the test set or of the unit under test. That type of information is included in the instruction manuals for the test sets and the specific equipment.

PURPOSES OF TEST EQUIPMENT

General purpose test sets are those items of test equipment used in the performance of a specific type of test on a variety of electrical equipment. In general, these sets include such items as meters, signal generators, oscilloscopes, vacuum tube and semiconductor testers, etc. Each of these types is available in a number of models; each with its own set of applications and limitations. One or more models of each basic type are normally available in each maintenance shop. The particular models available in a given shop are governed by the equipment to be supported.

Special purpose test sets are those items of test equipment used in the performance of a variety of tests on a specific type of electrical equipment.

MEASURING INSTRUMENTS

The term "measuring instruments," as used in this discussion, includes only that class of test equipment which measures the basic parameters of electrical equipment. The basic parameters are voltage, current, resistance, power, and frequency.

The discussion of measuring instruments includes test equipment classes designated as electronic voltmeters. The VTVM, which is an electronic voltmeter, is discussed in Aviation Electrician's Mate 3 & 2, NavPers 10348-C, and is not repeated here. Also nonelectronic meters such as ammeters, watt meters, and ohmmeters are discussed in Basic Electricity, NavPers 10086-B, and AE 3 & 2, NavPers 10348-C.

Electronic voltmeters discussed in this chapter are the phase angle voltmeter and the differential voltmeter.

PHASE ANGLE VOLTMETER

The overall accuracy of many electronic components is determined by measuring phase angles in computing transformers, computing amplifiers, and resolver systems. In the past, one of the most common methods used for measuring phase shift or phase angles between signals was observing patterns on an oscilloscope. With this method, it was hard to determine small angles, and difficult to translate various points into angles and sines of angles. The most limiting factor in using oscilloscope patterns developed when one of the signals contained harmonic distortion or noise.

In any complex waveform containing a fundamental frequency and harmonics, measuring phase shifts presents problems. In most applications, interest lies in the phase relationship of the fundamental frequency, regardless of the phase relationship of any harmonics which may be present. One of the requirements of a phase measuring device is to measure the phase difference between two discrete frequencies, regardless of the phase and amplitude of other components of the waveform.

The basic block diagram of a phase angle voltmeter is shown in figure 14-1. There are two inputs—the signal and the reference. Both channels contain filters which pass only the fundamental frequency. All other frequencies are highly attenuated. Each channel has a variable amplitude control and amplifiers to increase the variety of signals that can be checked.

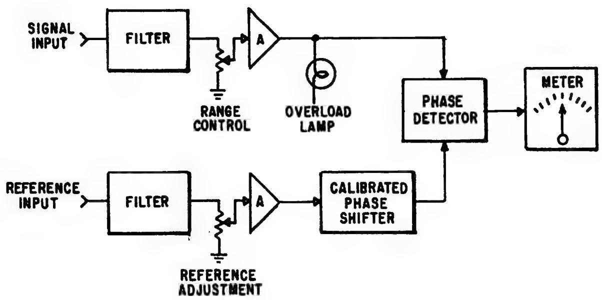

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Figure 14-1.—Phase angle voltmeter, block diagram.

A calibrated phase shifter is inserted into one channel; that channel signal can be phase shifted to correspond to the other channel. This is detected in the phase detector and observed on the meter.

The calibrated phase shifter is made up of a switch (whose position corresponds to the 0°, 90°, 180°, and 270° phase shift) and a potentiometer (whose dial is calibrated from 0° to 90°). The total phase shift is made up of the sum of the two readings.

The phase detector is a balanced diode bridge type demodulator. Its output is proportional to the signal frequency amplitude times the cosine of the angle of phase difference between the signal input and the reference input.

If the reference input is phase shifted until it is in phase or 180° out of phase with the signal input, the output from the phase detector is proportional to the signal input amplitude (the cosine of the angle is unity). If the reference input is phase shifted until it is 90° or 270° from the signal input, the phase detector output is zero (the cosine of the angle is zero).

The point at which the two signals are in phase or 180° out of phase is the point of maximum deflection on the meter. The difference between the in phase and the 180° out of phase points is in the direction in which the needle swings—not the distance it swings. As the point of maximum deflection is approached, the rate of change of the meter reading decreases because the cosine has a small rate of change near 0°. This makes it difficult to read the exact point of maximum deflection.

Because the cosine has a maximum rate of change as it approaches 90° (and thus gives a better indication on the meter), most commercial voltmeters are set to determine the point at which the signals are 90° out of phase—"quadrature." When the voltmeter is set for this point, there must be some way of converting the phase shifter reading so that it shows the correct amount of phase shift rather than 90° more or less than the actual amount. Some confusion exists in this area because different manufacturers have different methods of determining the signal quadrant. Manufacturers also differ on whether the final reading is a leading or a lagging phase shift. This means the electrician must be familiar with as many types of phase angle voltmeters as the Navy has in the field. He cannot assume that the method he uses to determine phase angle on one type of meter can be used on another; nor can he assume that, because one meter gives him a leading angle between signal and reference waveforms, another manufacturer's meter also gives leading phase shift.

DIFFERENTIAL VOLTMETER

The differential voltmeter is a reliable precision item of test equipment. Its general function is to compare an unknown voltage with an internal reference voltage, and to indicate the difference in their values. The differential voltmeter in most common use in Navy applications is the 803D/AD (fig. 14-2), manufactured by the John Fluke Co. The remaining portion of this discussion is based on that instrument.

The 803D/AD is useable as an electronic voltmeter, as a precision potentiometer, and as

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Figure 14-2.—Differential voltmeter, Model 803D/AD.

a megohmmeter. It can also be used to measure the excursions of a voltage about a reference value. Ease of operation, inherent protection from any accident overload, and high reliability of readings are additional advantages of the instrument. It is accurate enough for precision work in calibration laboratories, yet rugged enough for general shop use.

The heart of the unit is a precision 500-volt d-c reference power supply. This 500 volts

can be precisely divided into increments as small as 10 microvolts by means of 5 voltage dials. Unknown a-c or d-c voltages are matched against the precise internal voltage until no deflection occurs on the panel meter. The unknown voltage is then simply read from the voltage dials. In the highest null sensitivity range, a potential difference between unknown and reference voltage as small as 0.01 volts causes full scale meter deflection.

At null, the differential voltmeter presents an "infinite" input impedance to the voltage under measurement, almost completely eliminating circuit loading.

A functional schematic diagram of the differential voltmeter is shown in figure 14-3. The principal circuit divisions are as follows:

1. A 500-volt d-c reference power supply.
2. Precision voltage divider network.
3. VTVM.
4. Chopper-amplifier.
5. Converter and converter power supply.

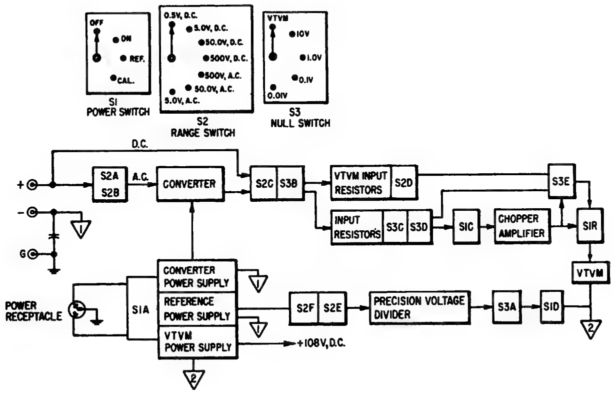

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Figure 14-3.—Differential voltmeter, functional schematic diagram.

The system circuitry is designed with two separate common returns. One of these, the return for the converter power supply and reference power supply, provides a safety factor for personnel and a capability for measuring a potential difference between two voltages. The other, which is the common return of the VTVM power supply, is connected to the known reference voltage output from the precision voltage divider network. This arrangement provides a constant d-c voltage of +108 volts across the differential amplifier regardless of the d-c potential applied to the grid.

D-C Reference Power Supply

A full wave rectifier with its associated filter network supplies a d-c voltage of approximately 1,000 volts to a conventional electron controlled voltage regulator. The regulated output is maintained at 500 volts ±0.01 percent.

In the 500 VDC position, the RANGE switch (S2E) passes this 500 volts directly to the precision voltage divider. In the 50 VDC, 5 VDC, and 0.5 VDC positions, range resistors controlled by S2F divide the reference voltage to 50, 5, and 0.5 volts d.c., respectively. In all a-c positions of the RANGE switch, only 5 volts of the reference supply is used, due to the fact that the maximum output of the a-c to d-c converter is 5 volts.

Precision Voltage Divider

Each of the four precision voltages available from the reference supply must be made adjustable through a precision divider string so that unknown voltages may be nulled or matched exactly. The five decade resistor strings (fig. 14-4 accomplish this function.

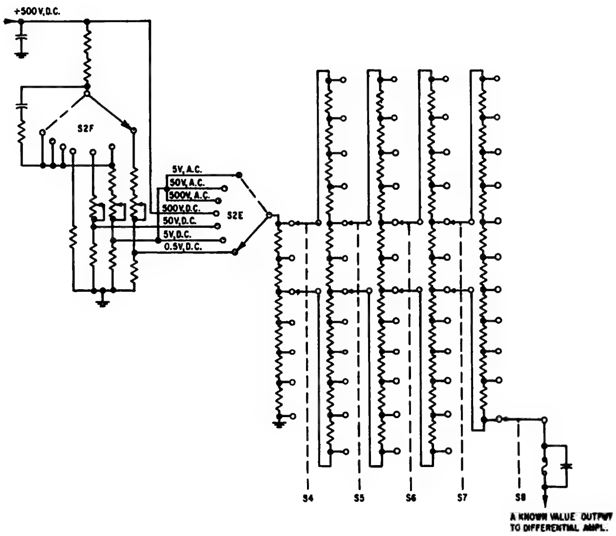

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Figure 14-4.—Precision voltage divider.

Note that each string, with the exception of the first, parallels two resistors of the string that precedes it. Between the two wipers of S4, there is a total resistance of 40K ohms and a total voltage of 100 volts d.c. with the RANGE switch in the 500 VDC position. Across the wipers of S5, S6, and S7, there are 10, 1, and 0.1 volts d.c., respectively. Switch S8 selects increment of 0.01 volt d.c. from the last decade. These voltages are reduced by a factor of 10 for each successively lower voltage range.

All resistors of each decade are matched and all decades are matched for each instrument, providing an overall divider accuracy of 0.005 percent.

With the NULL switch in any null range, the output of the precision voltage divider appears at the grid of one-half of the VTVM differential amplifier. A one two-hundredths ampere (5 milliampere) fuse protects this output.

Vacuum Tube Voltmeter

When operating in the differential mode, output voltage from the precision voltage divider appears on the grid of V4B, one-half of the differential amplifier. (See fig. 14-5.) The unknown voltage appears on the grid of V4A, the other half of the differential amplifier. Any difference between these potentials is indicated by the meter coupled between the cathodes of V4A and V4B. When the output voltage exactly matches the unknown, the meter reads zero and no current is drawn from the source being measured, because the same potential exists on both sides of the input resistances.

When used as a conventional VTVM, the grid of V4B is connected to the 0-volt bus, or negative binding post. With the range switch in the 0.5 VDC position, the unknown voltage appears directly on the grid of V4A and the meter indicates the approximate value of the unknown. Input divider resistors maintain the 0 to 0.5 grid voltage range for all instrument voltage ranges. The input resistance of the instrument in the VTVM position is 10 megohms.

Converter

All a.-c. measurements are made by first converting the a-c input to a d-c voltage. The converter provides a maximum d-c output of 5 volts for a maximum a-c input of 5 volts rms. In the 5 VAC position, range switch sections of S2A and S2B couple the converter

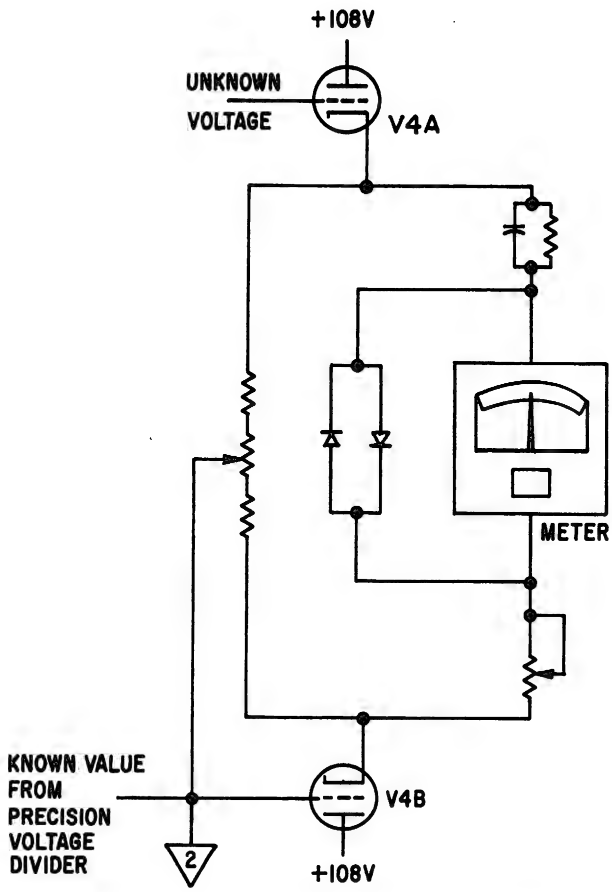

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Figure 14-5.—Differential amplifier.

amplifier input directly to the binding post. In the 50 VAC and 500 VAC positions, input attenuators reduce the unknown a.c. to provide a maximum of 5 volts a-c input to the first converter amplifier.

The overall frequency response of the converter is essentially flat from 30 Hz to 10 kHz.

GENERAL PURPOSE TEST EQUIPMENT

TRANSISTOR CURVE TRACER

The Transistor Curve Tracer, Type 575 is employed to plot or trace characteristic curves of transistors and other semiconductor devices. There are two major methods of plotting the characteristic curves of a transistor. One is to apply d-c voltages and make measurements point by point. The other method is to use

changing voltages and display the curve on an oscilloscope. (The 575 displays the curves on a self-contained oscilloscope.)

There are several advantages inherent in the use of the second method described, and they are as follows:

1. It is faster and more accurate than the point-by-point method.
2. The point-by-point method may allow small irregularities in the characteristics to go unnoticed; the dynamic method leaves no small gaps in the coverage.
3. Errors caused by heating are reduced due to the shorter periods of applied power; heat is a major factor in the operation of transistors.
4. Permanent records of the curves traced out on the oscilloscope may be easily produced at a reasonable cost through the use of photographic equipment.

The equipment also contains a self-checking capability. In case a displayed curve deviates from the published normal characteristic curve, the operator can quickly reassure himself of the accuracy of the test equipment.

The following paragraphs describe briefly the operational characteristics of the 575 and outlines a method for determining dial settings for testing transistors found in Navy equipment.

An illustration of the front panel of the equipment is shown in figure 14-6. The controls are grouped into five blocks, with a test connector panel at the base of the test set. In addition to the block arrangement, the panel is also color coded to simplify the operation. The collector currents and voltages are referenced by the sections of the panel etched in red; the sections etched in blue refer to the base currents and voltages. (An exception to this color code is noted when a common base transistor configuration is being tested; at that time the blue is in reference to the emitter.)

Functional Description

In the description of the five functional divisions that follows, refer to figure 14-6 for the item numbers listed; a functional block diagram is also given in figure 14-7.

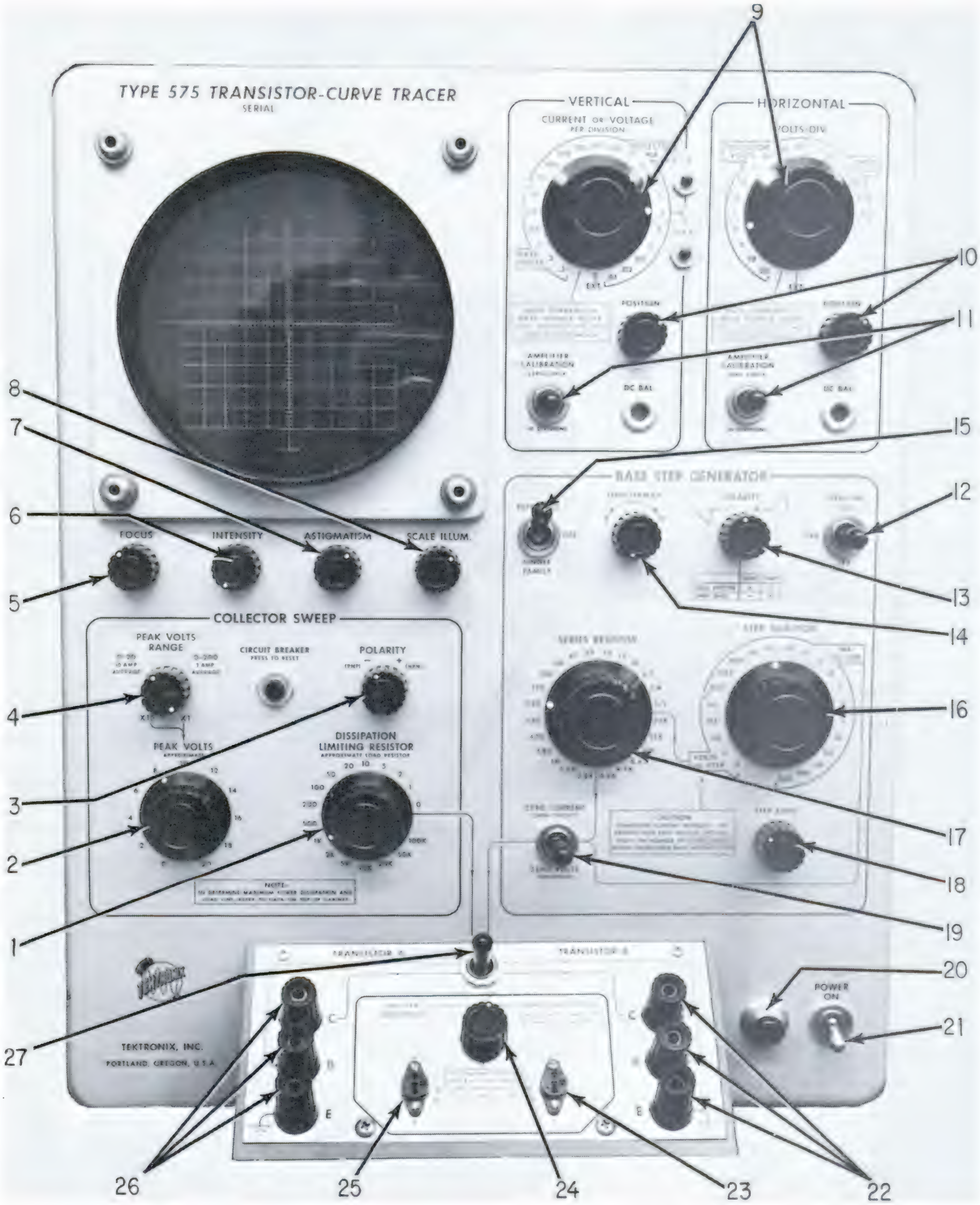
The collector sweep circuit supplies the transistor under test with a collector voltage which is the output of a full wave rectifier without any filtering. The 60-Hz line voltage is supplied to the full wave rectifier, and the output of the rectifier is 120-Hz pulses. The output waveform varies from 0 volts to some peak value which can be controlled from the front panel (items 2 and 4). The peak voltage can be varied in two ranges, from 0 to 20 volts and from 0 to 200 volts. The polarity of the sweep voltage can be reversed in order to check both PNP and NPN type transistors (item 3). A variable amount of resistance can be placed between the collector sweep supply and the transistor under test in order to limit the maximum amount of collector dissipation (item 1).

BASE STEP GENERATOR.—The step generator develops currents and voltages which change value, in stairstep fashion, in synchronization with the collector sweep voltage (items 12, 16, 17, and 18). The output of the generator can be reversed in polarity and can be connected to either the base or the emitter of the transistor under test (item 13). The number of steps can be varied from 4 to 12 according to the type of display desired (item 14).

DISPLAY FUNCTION.—The display function includes the three major functional blocks remaining—the vertical and horizontal amplifiers, and the cathode-ray tube. (A description of the operation of a cathode-ray tube is given in Basic Electronics; an oscilloscope is also discussed later in this chapter.)

The horizontal and vertical amplifiers of the cathode-ray tube display can be driven by several different inputs, depending upon what characteristics are of interest (item 9). The horizontal amplifier can select any of four inputs and display one of them on the horizontal axis. The four inputs are base volts, collector volts, base current or base source volts, and external. In the base volts position, the horizontal amplifier is connected to the base of the transistor under test. In the collector volts position, the horizontal amplifier is connected to the collector of the transistor under test. Both inputs have several positions so that the scale factor can be changed. The base current or base source volts position connects the output of the base step generator into the horizontal amplifier. The external position connects the horizontal amplifier to two coax connectors on the rear of the instrument.

The vertical amplifier can also select from four different inputs—collector MA, base volts, base current or base source volts, and external. Base volts, base current or base source volts, and external positions are the same as described for the horizontal amplifier; but in the collector MA position, the vertical axis gives a plot of collector current.



1. Dissipation limiting resistor.	10. Display position.	19. Zero current/voltage.
2. Peak volts control.	11. Amplifier calibration.	20. Indicator lamp.
3. Polarity switch.	12. Steps/sec selector.	21. Power ON-OFF.
4. Peak volts range.	13. Polarity switch.	22. Binding posts B.
5. Focus control.	14. Steps/family.	23. Socket B.
6. Intensity control.	15. Repetitive/single family.	24. Configuration switch.
7. Astigmatism control.	16. Step selector.	25. Socket A.
8. Scale illumination.	17. Series resistor.	26. Binding posts A.
9. Vertical/horizontal select.	18. Step zero.	27. Comparison switch.

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Figure 14-6.—Transistor curve tracer (Tektronix 575).

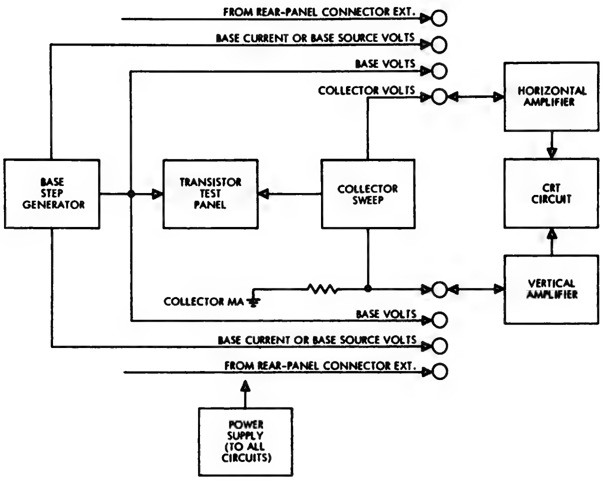

Figure 14-7.—Transistor curve tracer block diagram. AE.701

INTERPRETING THE DISPLAY.—As the collector voltage changes from zero to some peak value and back to zero again, the step generator output remains at some specific level and then changes to some new level for the next collector voltage cycle. The collector voltage is swept at a rate of 120 Hz and the step generator changes steps or level after every cycle (in the 240 steps per second, the step generator changes at both the zero point of the collector sweep and at the maximum point). Figure 14-8 is a plot of collector

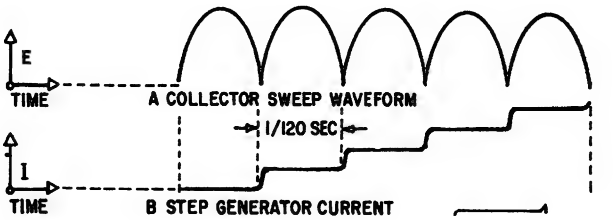

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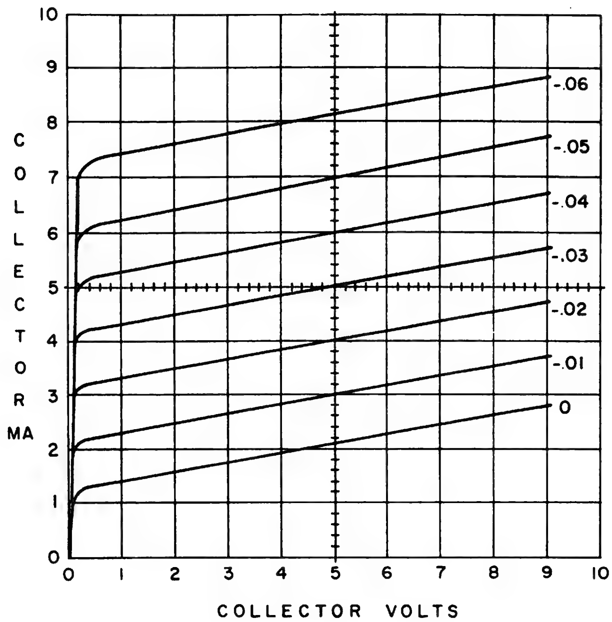
Figure 14-8.—Waveforms of collector sweep versus step generator current.

sweep voltage and base step generator current. It should be noted that the collector sweep makes a complete excursion, while the base is at some steady value. As the next collector sweep starts, the base current is changed to the next value of current selected by the dials on the front of the instrument, and again the base current will remain steady while the collector voltage is varied.

As previously mentioned, the waveforms of figure 14-8 can be reversed by switches on the front panel in order to check either PNP or NPN type transistors.

Figure 14-9 is a plot of collector voltage and collector current for given values of base current for an NPN transistor. For this type of transistor, it is a convention to have the lower left-hand corner represent zero collector voltage and current. In this graph, it was arbitrarily decided that each division to the right of the lower left hand corner of the horizontal axis would represent a collector voltage change of one more volt positive. This would indicate a collector voltage swing of 0 to 10 volts positive. The vertical axis is a



AE.703
Figure 14-9.—Typical NPN collector curves.

plot of collector current varying from 0 milliamperes in the lower left-hand corner to 10 milliamperes at the top of the graph in 1 milliampere steps. The different lines on the graph represent different values of base current; in this case, each line represents a change of 0.01 milliampere. (If this graph had been for a PNP rather than for an NPN, the upper righthand corner would have represented zero collector voltage and zero collector current.

The divisions to the left would have represented negative collector voltage, and the divisions downward from the top would have indicated the amount of negative current. This would have made the family of curves to appear as shown in figure 14-10.

These curves are known as the static collector characteristics for a common emitter configuration or output characteristic curve. Curves can be developed for common base and common collector also, but normally the information is available for the common emitter mode. Using this configuration, it is easier to check the transistor. To thoroughly describe how a transistor is going to work in a circuit, it is necessary to know the input characteristic curve as well as the output curve. The input characteristic curve is developed by plotting base current on the horizontal axis, base to emitter voltage (V_{RE}) on the vertical axis at different values of collector to emitter voltage (V_{CE}). Although it is necessary for the design engineer to know the input characteristic curve when designing a circuit, the output characteristic curve normally provides sufficient information to evaluate a transistor.

Measuring Beta (h_{fe})

One means of measuring the quality of a transistor is the beta (β) or current gain in the common emitter configuration. Mathematically, beta is represented by the formula

$$\beta = \frac{\Delta\, ic}{\Delta\, ib}$$

where V_{CE} is constant. Beta is also called the forward current transfer ratio represented by the symbol h_{fe}, which is derived from the hybrid equivalent circuit of a transistor. To determine the beta from the output characteristics, it is necessary to measure the change in collector current between two values of base current at some constant collector voltage. For instance, to determine the beta at a collector voltage of 5 volts, measure the change in collector current between the base current curves of 0.02 ma and 0.03 ma (fig. 14-9). In this example, the change in collector current measures 1 ma, so the beta is equal to the change in collector current divided by the change in base current or

$$\frac{1 \times 10^{-3}}{0.01 \times 10^{-3}} = 100$$

Measuring I_{CO}

Another characteristic of a transistor is the I_{CO}, also called I_{CBO}. This is the collector current when the collector is biased in the reverse direction (high resistance, normal connection) with respect to the base, and the emitter is open circuited. The I_{CO} of a transistor is highly temperature-dependent, and the measurement made with the curve tracer is at the ambient temperature only; but it is still significant. The method used to measure the I_{CO} is shown schematically in figure 14-11. Notice that the emitter is not connected.

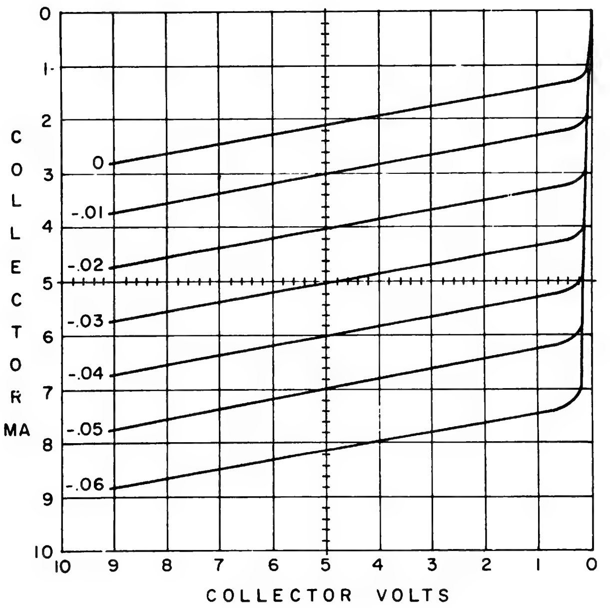


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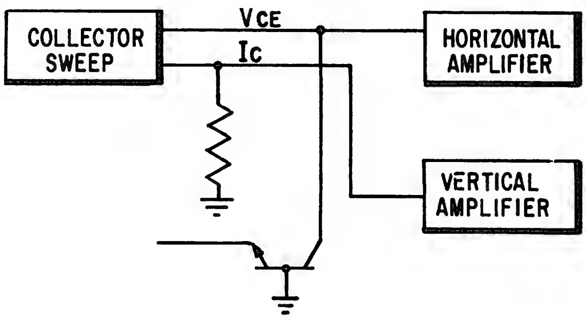
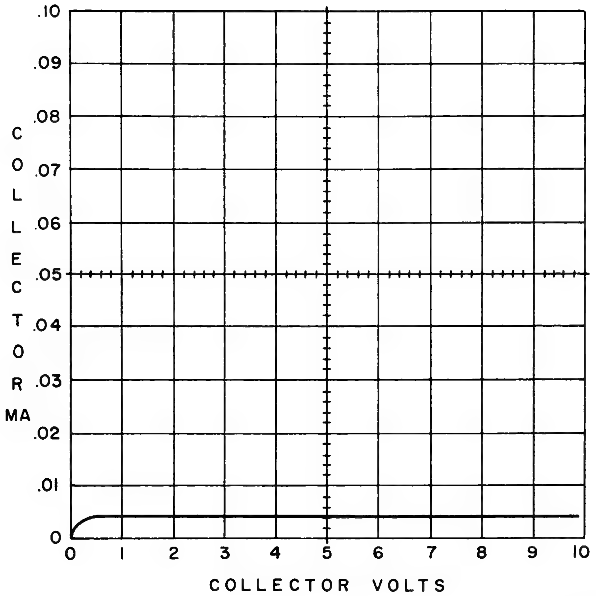
Figure 14-10.—Typical PNP collector curves.



AE.705

Figure 14-11.—Connections for checking $I_{CO}(I_{CBO})$.

The display of the curve tracer when measuring I_{CO} is shown in figure 14-12. The vertical axis indicates collector current, just as it did when beta was being measured; but now the vertical amplifier is adjusted to afford maximum gain so that the small amount of current causes a noticeable deflection. The horizontal axis is still calibrated to show collector voltage.



AE.706

Figure 14-12.—Typical display of $I_{CO}(I_{CBO})$.

The electrician must know the beta and I_{CO} of a transistor in order to determine if the one he is testing is good. Since no manual describing the characteristics of different transistors is provided with the curve tracer, it is necessary to obtain this information from other sources. NA16-1-530, Replacement Guide, Semiconductor Device (Transistors and Semiconductor Diodes), dated May 1963, is an excellent source. For those transistors not listed in this publication, a specification sheet can be obtained from the manufacturer.

Section 1A of NA16-1-530 is a list of transistor replacements. Section 1A also gives the technical section in which a specific transistor is listed. These are Sections 2 through 10. To use this manual, look up the transistor in the technical section which applies; descriptions at the top of each page tell whether the transistor is germanium or silicon, PNP or NPN, low or high power. The important columns in the technical section needed to obtain information on testing are MAXIMUM COLLECTOR DISSIPATION, ABSOLUTE MAX RATINGS, MAX I_{CBO} at MAX V_{CB}, Typical "h" Parameters at 25°C.

Under the column labeled Typical "h" Parameters, there is listed a typical h_{fe} or a minimum and maximum value of h_{fe}, depending on the technical section in which the transistor is listed. In the same column is listed the collector voltage and collector current at which this h_{fe} is to be obtained.

The collector voltage (V_{CE}) and collector current (I_C) provide the starting points from which to determine the curve tracer settings; for instance, if the V_{CE} is 5 volts, the horizontal amplifier would be set to COLLECT VOLTS, 1 VOLT PER DIVISION. This would place the 5-volt position in the middle of the display; and if the I_C is 1 ma, the vertical amplifier would be set to COLLECT MA, 0.2 MA PER DIVISION. This would place the 1-ma position in the middle of the display. The collector sweep can be determined from these settings, since the horizontal amplifier is set to 1 volt per division. The collector voltage varies a total of 10 volts, so the PEAK VOLTS RANGE is in the 0-20 position and the PEAK VOLTS control is set at 10. To determine the setting for the DISSIPATION LIMITING RESISTOR, obtain the maximum collector dissipation from the column in the technical section labeled MAX COLL DISS. This, in conjunction with the setting of the PEAK VOLTS control, can be plotted on the chart on top of the curve tracer to obtain the correct setting of the limiting resistor.

The step generator is set up in the following manner: The switch labeled REPETITIVE-OFF-SINGLE FAMILY is set to REPETITIVE, and the control labeled STEPS/FAMILY is set counterclockwise. This gives four steps per family, which is usually sufficient; if more are desired, set STEPS/FAMILY to any value. Under the switch labeled POLARITY is a chart showing the correct position for NPN and PNP. Use the portion of the chart pertaining to grounded emitter type circuits. The switch labeled STEPS/SEC can be in either of the two 120 positions, or in the 240 position. The only difference in the two 120 positions is that at one of them the step generator changes level when the collector is at zero volts; at the other position, the step generator changes level when the collector is at the maximum voltage. In the 240 position, the step generator changes level at both the

zero collector voltage and at the maximum point. The step selector can be set by starting at the smallest change per step (0.001 ma) and increasing the size of the step until the display has the necessary separation between the values of base current to determine beta. In the alternative procedure, the beta listed in the technical section can be divided into the amount of collector current and the result used as the setting of the step selector. If there is not enough separation between the lines representing the base current to accurately determine the beta, increase the amount of each base step until a good display is obtained.

To check the I_{CO} of the transistor, disconnect the emitter and change the current per division setting on the vertical amplifier to the most sensitive position (0.01 ma). Set the step zero very accurately, as described in NA16-45-107 (the Service Instruction Manual and Operating Instruction Manual for the curve tracer). After setting the step zero, note the difference between the step zero and the present position of the trace; this is an indication of the I_{CO}. The I_{CO} of the transistor is listed in the technical section, in the column MAX I_{CBO} at MAX V_{CB}, which describes the I_{CO} at BV_{CBO}—the breakdown voltage, collector-to-base with emitter open. By measuring beta and I_{CO}, a fair picture of the condition of a transistor is presented.

Matching of transistors should also be mentioned in connection with the curve tracer. Some Navy equipments have matched pairs of transistors, but unless the specifications are checked, it cannot be automatically assumed that betas of the transistors are matched. Sometimes the betas are matched, sometimes they are not; many times several characteristics are matched.

SIGNAL GENERATORS

The principal function of a signal generator is the production of signals having the specific characteristics required for the test or measurement in question. It is very important that the amplitude of the generated signal be correct. In many generators, output meters are included in the equipment so that the output may be adjusted and maintained at a standard level over a wide range of frequencies.

When using the generator, the test equipment output signal is coupled into the circuit being tested. Its progress through the equipment may then be traced by the use of high impedance indicating devices such as vacuum tube voltmeters or oscilloscopes. In many signal generators, attenuators are provided. These are used to regulate the voltage of the output signal and also provide correct impedance values for matching the input impedance of the circuit under test. Accurately calibrated attenuators are desirable since the signal strength must be regulated to avoid overloading the circuit receiving the signal.

There are many types of sinusoidal signal generators. It is possible to classify them roughly by frequency into audio generators, generators of both the audio and video ranges; radiofrequency generators, frequency-modulated RF generators, and special types which combine all of these frequency ranges.

In addition, signals other than sinusoidal are also generated for testing of equipment. The signal generators producing nonsinusoidal outputs are usually classified according to the type of signals they produce. Some signal generators produce several types of signal waveforms.

In almost all currently used types of signal generators, electron tube oscillators are used to produce the initial signal. In order to achieve accurate results in the use of the signal source, it is necessary to allow the oscillator circuits to reach a condition of stable operation before applying the output. This condition is reached when the tubes and circuit elements attain the temperature at which the instrument was calibrated.

A preliminary warmup should always be given the generator when accurate and stable signals are desired. The minimum warmup time for the generator is contained in the Service Instruction Manual for each model. The general properties and functions of signal generators are covered in Basic Electronics.

CATHODE-RAY OSCILLOSCOPE

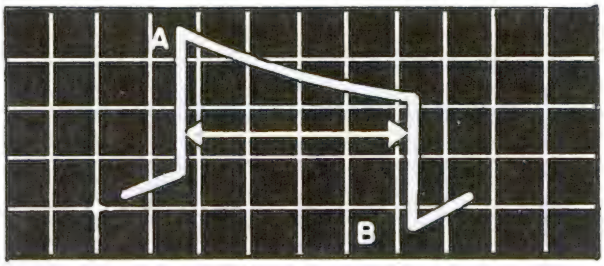
An oscilloscope is an electronic test set that displays information on the face of its cathode-ray tube (CRT). It is sometimes referred to as an "O scope." The uses of an oscilloscope are many and varied, but it is used primarily to troubleshoot and aline electronic equipment; which is accomplished by observing and analyzing waveforms as to shape, amplitude, and duration. The Service Instruction Manual for the particular equipment on which work is being performed will designate what waveforms are

to be observed at the various test points throughout the equipment. Waveforms that will be observed at any one selected test point will differ, depending on whether the operation of the equipment is normal or abnormal.

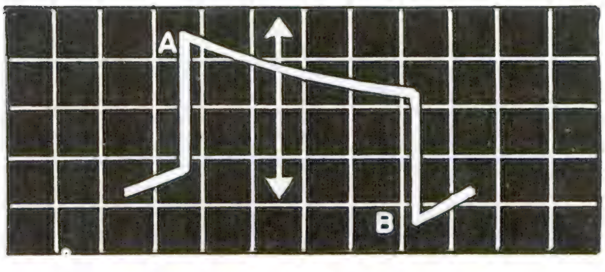
Waveforms and Their Oscilloscopes Displays

The display observed on a cathode-ray oscilloscope is ordinarily one such as shown in figure 14-13. This illustration shows the instantaneous voltage of the wave plotted against time. Elapsed time is indicated by horizontal distance, from left to right, across the etched grid (graph) placed over the face of the tube. The amplitude of the wave is measured vertically on the graph.

The oscilloscope is also used to picture changes in quantities other than simply the voltages in electric circuits. If an electric current waveform is of interest, it is usually satisfactory to send the current through a small series resistor and to look at the voltage wave across the resistor with the oscilloscope. Other quantities such as temperatures, pressures, speeds, and accelerations can be translated into voltages by means of suitable transducers; and then viewed on the oscilloscope.



(A)



(B)

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Figure 14-13.—Typical waveform display; (A) measurement of elapsed time (B) measurement of voltage difference.

INTERPRETING THE DISPLAY.—To find the elapsed time between two points on the graph (fig. 14-13 (A)) such as A and B, multiply the horizontal distance between these points in major graduated divisions by the setting of the TIME/DIV (time per division) control. This control sets the horizontal sweep rate of the oscilloscope. The distance between points A and B is 4.4 major divisions. If the TIME/DIV control is set at 100 microseconds per division, then the elapsed time between points A and B must be 4.4 x 100 = 440 microseconds. In general, elapsed time = horizontal distance in divisions X TIME/DIV setting.

If a MULTIPLIER control is associated with the TIME/DIV control, multiply the above result by the setting of the MULTIPLIER. If a MAGNIFIER is in operation, divide the result by the amount of magnification.

To find the voltage (fig. 14-13 (B)) difference between any two points on the graph, such as A and B, multiply the vertical distance between these points in major graduated divisions by the setting of the VOLTS/DIV control, which sets the vertical deflection factor or "sensitivity" of the oscilloscope. The vertical distance between points A and B is 3.6 divisions: If the VOLTS/DIV control is set at 0.5 volts per division, then the voltage difference between points A and B must be 3.6 x 0.5 = 1.8 volts. In general, voltage difference = vertical distance in divisions x VOLTS/DIV setting.

The quantity called pulse repetition rate (or pulse repetition frequency) for periodic pulses can be expressed as the number of pulses per unit of time. EXAMPLES: 10 pulses per second; 50 pulses per microsecond.

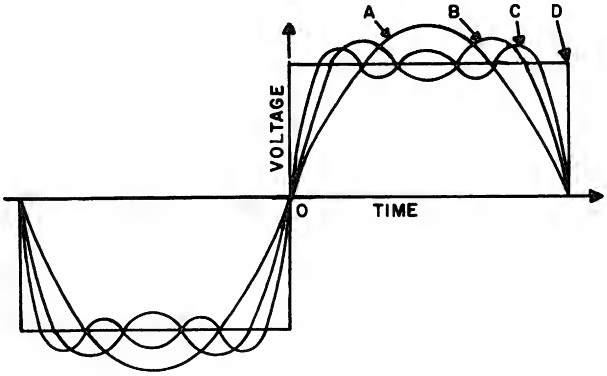
In using the oscilloscope to measure the frequency or repetition rate of periodic waveforms, first read the horizontal distance in major divisions between corresponding points on two succeeding waves. This is the horizontal distance occupied by one cycle of the wave. Multiply this by the setting of the TIME/DIV control in seconds, milliseconds, or microseconds. Take the reciprocal of this product; that is, divide it into 1. The result is the desired frequency or repetition rate in pulses per second, per millisecond, or per microsecond.

It is convenient to use square waves, rather than other forms of waves, for testing of equipment because the nature of a defect, rather than simply its presence, is suggested by the kind of distortion which occurs to a square wave. By observing squarewave response, it is easy to tell whether the transmission of low or high frequencies is affected. This observation is not so well separated with regard to frequency if waves other than square waves are used.

If two linear devices give identical responses when square waves are fed into them, they can, in general, be expected to give responses similar to each other when other waveforms are fed into them.

INFORMATION CONTAINED IN A SQUARE WAVE.—It can be shown that a periodic wave contains the following components: (1) a fundamental wave, which is a sine wave having a frequency equal to the repetition frequency of the square wave, and (2) an infinite series of harmonics—sine waves having frequencies which are equal to whole numbers multiplied by the fundamental frequency. The harmonics must be properly related in phase and in amplitude to the fundamental.

Waveform D of figure 14-14 depicts a periodic rectangular wave (square wave). In the case of the square wave, the only harmonics present are the "odd" harmonics (those whose frequencies are equal to the fundamental frequency multiplied by odd whole numbers); and the strengths of the harmonics vary in inverse proportion to the frequencies of the harmonics, the fifth harmonic being one-fifth as strong as the fundamental, for example. The way in which these waves combine to make up a square wave is suggested by figure 14-14.



AE.708
Figure 14-14.—Addition of harmonics to fundamental waveform.

Curve A shows the fundamental sine wave, curve B the sum of the fundamental and third harmonic, curve C the sum of the fundamental plus third and fifth harmonics. The ultimate square wave is waveform D.

It will be noted that the first few harmonics combine with the fundamental to provide an approach to an actual square wave. Additional harmonics, of higher frequencies, would (a) cause the leading edge of the wave to rise more rapidly, and (b) produce a sharper corner between the leading edge and the top of the wave. It would require an "infinite" range of harmonics to produce a truly vertical leading edge and an actual sharp corner, and this situation is physically impossible to produce. But waves can be generated which are very close to this ideal situation. (The same considerations apply to the falling edge of the waveform, and the following corner.)

Information regarding the amplitude and phase relationships of the higher harmonics is, then, contained in the leading-edge steepness and in the sharpness of the corner.

If low frequency components (fundamental and the first few harmonics) are not present in the proper amounts and in the correct phase relationships, the part of the square wave affected will be the flat top. Figure 14-15 (A) shows the location of the low and high frequency information in a square wave. Low frequency defects will appear in the form of slope or general curvature in the top, as shown in (B) and (C) of the figure. In (B) of the figure, the low frequency components have leading phase angles and are attenuated. In (C) the low frequency components have lagging phase angles and are accentuated.

OSCILLOSCOPE BLOCK DIAGRAM.—Figure 14-16 is a block diagram of a typical oscilloscope, omitting power supplies. The waveform (A) to be observed is fed into the vertical amplifier input. The calibrated VOLTS/DIV control sets the gain of this amplifier. The push-pull output (B and C) of the vertical amplifier is fed through a delay line to the vertical deflection plates of the cathode-ray tube.

The time base generator or "sweep generator" develops a sawtooth wave (E) that is used as a horizontal deflection voltage. The rising or positive-going part of this sawtooth, called the "runup" portion of the wave, is linear. That is, it rises through a given number of

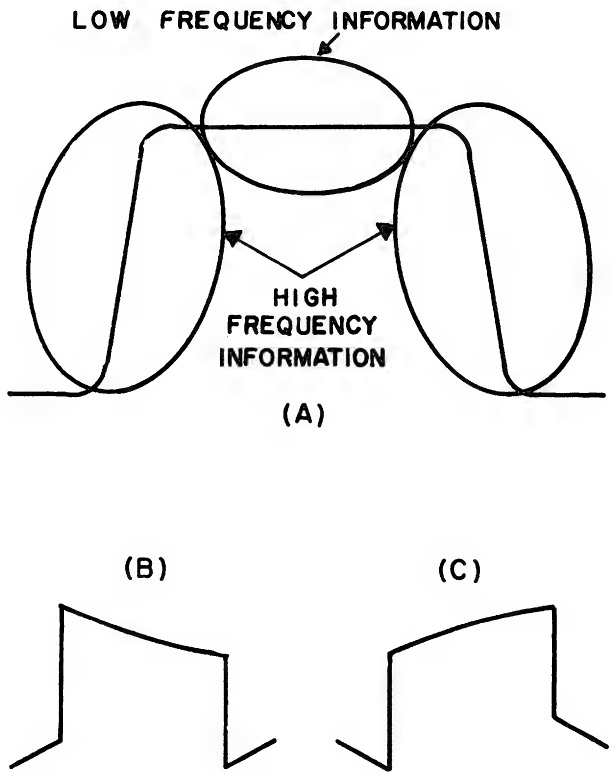


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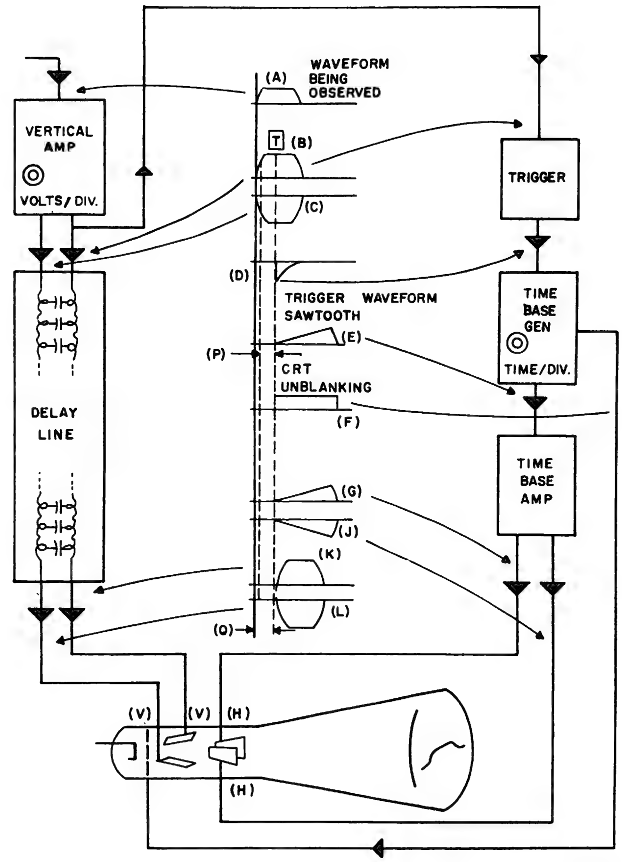
Figure 14-15.—Information found in a square wave.



AE.710

Figure 14-16.—Typical oscilloscope block diagram.

volts during each unit of time. This rate of rise is set by the calibrated TIME/DIV control. The sawtooth voltage is fed to the time base amplifier. This amplifier supplies two output sawtooth waveforms (G and J) simultaneously—one of them positive-going, like the input, and the other negative-going. The positive-going sawtooth is applied to the right-hand horizontal deflection plate of the cathode-ray tube, and the negative-going sawtooth is applied to the left-hand deflection plate. As a result, the cathode-ray beam is swept horizontally to the right through a given number of graduated divisions during each unit of time, the sweep rate being controlled by the TIME/DIV control.

In order to maintain a stable display on the cathode-ray tube screen, each horizontal sweep must start at the same point on the waveform being displayed. To accomplish this, a sample of the displayed waveform is fed to a "trigger" circuit which gives a negative output voltage spike (D) at some selected point on the displayed waveform. This triggering spike is used to start the rising portion of the time base sawtooth. As far as the display is concerned, then, "triggering" can be taken as synonymous with the starting of the horizontal sweep of the trace at the left-hand side of the grid.

A rectangular "unblanking" wave (F) derived from the time base generator is applied to the grid of the cathode-ray tube. The duration of the positive part of this rectangular wave corresponds with the duration of the positive-going or rising part of the time base output, so that the beam is switched on during its left-to-right travel and is switched off during its right-to-left retrace.

In many cases the leading edge of the waveform being displayed is used to actuate the trigger circuit. Yet it may be desirable to observe this leading edge on the screen—and

the triggering and unblanking operations require a measurable time (P), often about 0.15 microsecond. To permit the leading edge to be seen, a delay (Q) of about 0.25 microsecond is introduced by the delay line in the vertical deflection channel after the point where the sample of the vertical signal is tapped off and fed to the trigger circuit.

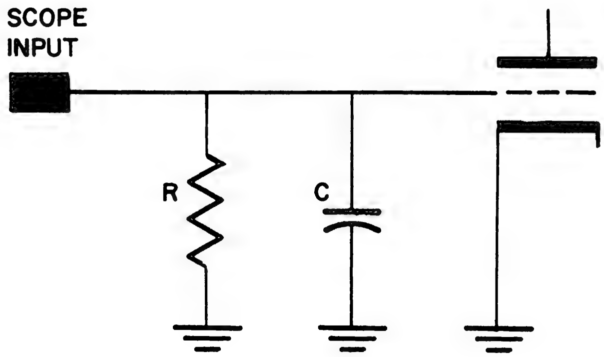
The purpose of the delay line is to retard the application of the observed waveform to the vertical deflection plates until the trigger and time base circuits have had an opportunity to begin the unblanking and horizontal-sweep operations. This permits viewing the entire desired waveform—even though the leading edge of that waveform was used to trigger the horizontal sweep.

If the delay line were not used, only that portion of the waveform following the instant (T) in waveform (A) could be seen.

Oscilloscope Probe

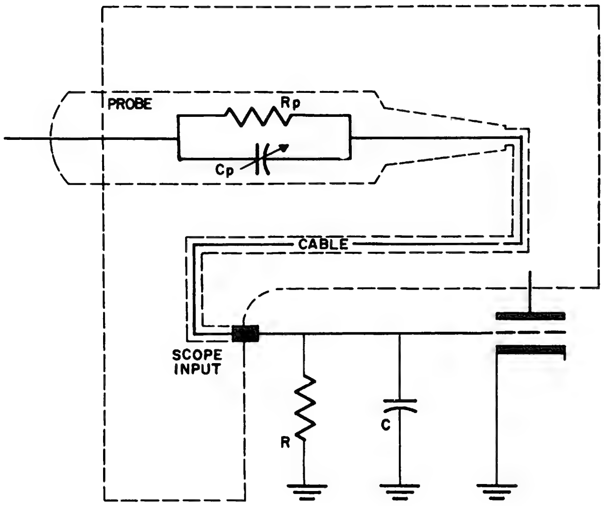
The input circuit to the vertical amplifier of an oscilloscope can be simulated by a high resistance R shunted by a small shunt capacitance C, as shown in figure 14-17.

In some applications, even this high resistance and small capacitance can produce undesirable loading upon the circuit whose waveforms are being examined by means of the oscilloscope. This loading can cause the oscilloscope presentations to be different from the waveforms that would be present with the oscilloscope disconnected. One use of a passive probe is to reduce this resistive-capacitive loading on the circuit under investigation.



AE.711
Figure 14-17.—Oscilloscope vertical amplifier input circuit.

The probe includes a resistor R_p shunted by a capacitor C_p (fig. 14-18). This combination is connected in series with the inner conductor of the cable to the oscilloscope input. The result is that, when the probe is connected to the circuit under investigation, there is connected to that circuit a new effective loading capacitance smaller than the original capacitance C and a new effective loading resistance larger than the original resistance R. Thus the loading effect of the oscilloscope input-circuit on the circuit under investigation is reduced through the use of the probe.



AE.712
Figure 14-18.—Oscilloscope vertical amplifier using a passive probe input.

A second effect of the probe is to reduce the amount of signal voltage applied directly to the oscilloscope input connection for a given amount of original signal voltage. This occurs because of the voltage-divider action of R_p and R. This effect is taken into account in the "attenuation ratio" marked on the probe. Thus if the probe is marked "10X ATTEN" all oscilloscope voltage indications must be multiplied by 10.

If an oscilloscope equipped with a probe is used to look at a square wave, and the probe capacitor C_p is too small, some of the high frequency components of the square wave will be bypassed around the oscilloscope input terminals by the input capacitance C. Thus the steepness of the leading edge of the displayed square wave is reduced. (See fig. 14-19 (A).)

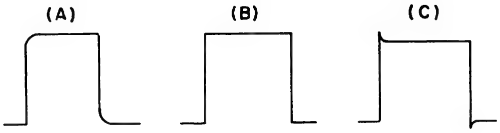


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Figure 14-19.—Effects of probe adjustment.

If the probe capacitor is adjusted to the correct value, a compensating amount of high frequency information is bypassed around the probe resistor R_p to make up for the loss through C, and the leading edge of the displayed square wave will be restored to its original steepness (B). If C_p is made too large, the high frequency response of the circuit will be over-compensated and apply too much high frequency information to the oscilloscope input connection. This results in an overshoot in the displayed waveform that was not present in the original (C). C_p can be adjusted to its correct value by using the probe to display the square wave generated by the voltage calibrator that is a part of the oscilloscope. Adjustment is made to display a square wave with as flat a top as possible.

Probe adjustment must be checked whenever a probe is used with an oscilloscope or a plug-in preamplifier that has an input capacitance different from that of the instrument with which the probe was previously used.

NOTE: As indicated in figure 14-18, the attenuation achieved is a result of R as well as R_p, which means that, though probes may be swapped for use with other types of oscilloscopes, the calibration may be in error, even though waveform distortion may possibly be adjusted out.

Oscilloscope AN/USM-140B

The front panel arrangement of a dual-channel oscilloscope that was especially designed for general purpose use is shown in figure 14-20. Most of the controls and connectors normally used by the operator are indicated in the figure and are self-explanatory. Those that are not, are listed and described below.

CALIBRATOR SWITCH (item 2). This switch is used to control the output of the self-calibrator which supplies a 1-kHz signal used as a standard to check the accuracy of the vertical and horizontal sensitivity selectors. The signal is available at either of the two connectors just below the switch depending on the amplitude required. Amplitude of the signal is controllable from 0.2 millivolts to 100 volts.

ASTIGMATISM CONTROL (item 7). This control adjusts the sharpness of the trace. It is used in conjunction with the focus control.

POLARITY SWITCH (item 9). This switch selects direction of beam deflection for channel A presentation. Channel B has an identical control.

AC-DC SWITCH (item 11). This switch selects the type of input coupling. Either capacitive for a-c signals or direct for d-c signals. Channel B has an identical control.

GATE OUTPUT (item 14). The gate output provides a +50-volt unblanking pulse during horizontal sweep time.

SWEEP OUTPUT (item 16). The sweep output provides a voltage ramp of approximately -50 to +50 volts coincident with the horizontal sweep.

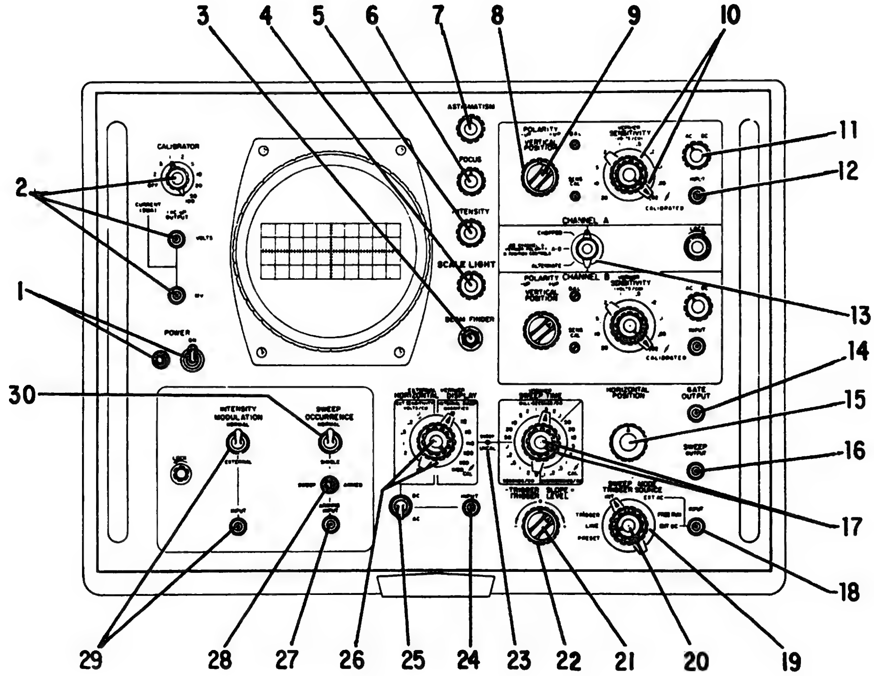
TRIGGER SOURCE (item 19). The trigger source selects the source of the signal to be used to trigger the sweep.

SWEEP MODE (item 20). The sweep mode provides a variable sensitivity adjustment for the sweep circuit. It also allows for the selection of either a triggered or a free running sweep.

TRIGGER SLOPE SWITCH (item 21). This switch selects the portion of the waveform used to trigger the sweep either positive or negative.

This instrument is a high speed, precision oscilloscope for displaying the waveforms of electrical voltages that range from a frequency of 22 megahertz to direct current. Vertical deflection sensitivity ranges from 20 millivolts to 200 volts per centimeter. Horizontal deflection sensitivity ranges from 0.1 volt to 100 volts per centimeter at frequencies from direct current to 1 megahertz.

The sweep generator, which is a part of the horizontal deflection system, provides a variable range of sweep times to allow the operator to display one or several cycles of the waveform, as required. The sweep rates are adjustable from 0.1 microsecond to 5 seconds per centimeter. A vernier control in the sweep circuit can be used to extend the slowest sweep to 15 seconds per centimeter. The sweep can be synchronized by an external signal or by the signal being viewed. Polarity and sensitivity of synchronization are selectable to permit synchronization from different points on complex



AE.714

1. Power ON-OFF/indicator lamp.
2. Calibrator switch and connectors.
3. Beamfinder.
4. Scale illumination.
5. Intensity control.
6. Focus control.
7. Astigmatism control.
8. Vertical position.
9. Polarity switch.
10. Sensitivity switch.
11. A.c.-d.c. switch V.
12. Channel A input.
13. Channel selector.
14. Gate output.
15. Horizontal position.
16. Sweep output.
17. Sweep time.
18. External trigger.
19. Trigger source.
20. Sweep mode.
21. Trigger slope.
22. Trigger level.
23. Sweep uncal.
24. Horizontal input.
25. A.c.-d.c. switch H.
26. Horizontal display.
27. Arming input.
28. Sweep armed.
29. Intensity modulation.
30. Sweep occurrence.

Figure 14-20.—Oscilloscope AN/USM—140B.

waveforms. Sweep rate, sweep expansion, and sensitivity are direct reading controls and are provided with potentiometer type continuous adjustment between each of the calibrated step selections.

Two identical probes with a 10 to 1 attenuation are provided in addition to an assortment of connector adapters and two coaxial cables to facilitate connecting the oscilloscope to the variety of equipment with which it can be used.

Maintenance of the oscilloscope by operating personnel is limited to checking and adjusting vertical sensitivity and balance, cleaning the air filter in the cooling air inlet, and replacing fuses. In many cases a calibration adjustment is required when replacing tubes and semiconductors. Therefore, only qualified personnel should attempt replacement of such parts. Operating personnel other than those qualified to make calibration adjustments should refrain from repair of this type except in an emergency.

The useful life of an oscilloscope can be materially extended by using normal care in handling and operating. When in use, the area behind the cooling air inlet must be kept clear to allow free flow of the cooling air through the ventilating door. This oscilloscope is provided with a thermal switch to protect from overheating. If the instrument goes off during use, removal of the dual trace preamplifier plug-in unit will allow the operator to view a neon type indicator lamp. If the lamp is lit, the oscilloscope is overheated. Turn off the power and investigate the cause of overheating.

CAUTION: This instrument contains voltages as high as 8,600 volts, which can be fatal. Turn the instrument off before touching any internal part.

TEST SETS

SYNCHRO ALIGNMENT SET TS-714/U

The Synchro Alignment Set TS-714/U (fig. 14-21) is a portable test set used to check the alinement of synchros or resolvers. It can be used to aline any 400 Hz synchro or resolver. In addition to its higher sensitivity, the test set has an additional advantage over the methods previously discussed in that the test set can also supply excitation voltage for the synchro or resolver being alined.

The test set basically consists of a bandpass amplifier and power supply, a synchro or resolver excitation supply with outputs from 3 to 115 volts rms (1, fig. 14-21) and switching circuits. The output voltages from the synchros or resolvers are applied to the amplifier, the output of which is fed to a phase sensitive detector circuit. The detector's output is metered by the microammeter (2). A meter switch (3) selects the meter sensitivity from 300 volts full scale to 0.1 volt full scale, plus a calibrate and off position.

The meter has a ZERO center scale and indicates 0 when the synchro or resolver is adjusted to either of its two nulls. The synchro or resolver is adjusted to a null position with the function switch (4) in the ZERO position. When the null is reached, the function switch is switched to the POL position and note is taken of the meter reading. Then the function switch

AE.715

1. Excitation switch.
2. Microammeter.
3. Meter sensitivity switch.
4. Function switch.

Figure 14-21.--Synchro Alignment Set TS-714/U front panel.

is returned to ZERO position and the synchro is rotated 180° to its opposite null. When the opposite null is reached, the function switch is again switched to the POL position and a note made of the reading. The correct null will be the one indicating the lowest reading with the function switch in the POL position. When the synchro is adjusted to this null, it is electrically zeroed with the correct polarity.

For detailed instructions on the use of the TS-714/U, consult Operation and Service Instruction Manual, NA 11-70-FAG-510.

APPROACH POWER COMPENSATOR TEST SET

The approach power compensator test set (CV 21-206611-1) (fig. 14-22) is used to perform flight line tests of the approach power compensator systems installed in F-8 aircraft series.

The test set simulates angle of attack, accelerometer, and integrator balance signals, and feeds these signals to the system under test. The test set monitors the response of the individual components of the system to these simulated signals while the components are connected as a system. The test set cannot be used to test individual components that are disconnected from the system. Use of the test set is limited to the checkout of the following:

1. Servoamplifier.
2. Servoactuator.
3. Computer.
4. Accelerometer.
5. Angle-of-attack.
6. Wind transducer.

For detailed operation of the test set refer to NW 17-15CAM-2.

AE.716

Figure 14-22.—Approach power compensator flight line test set.

ATTITUDE HEADING REFERENCE SYSTEM ANALYZER

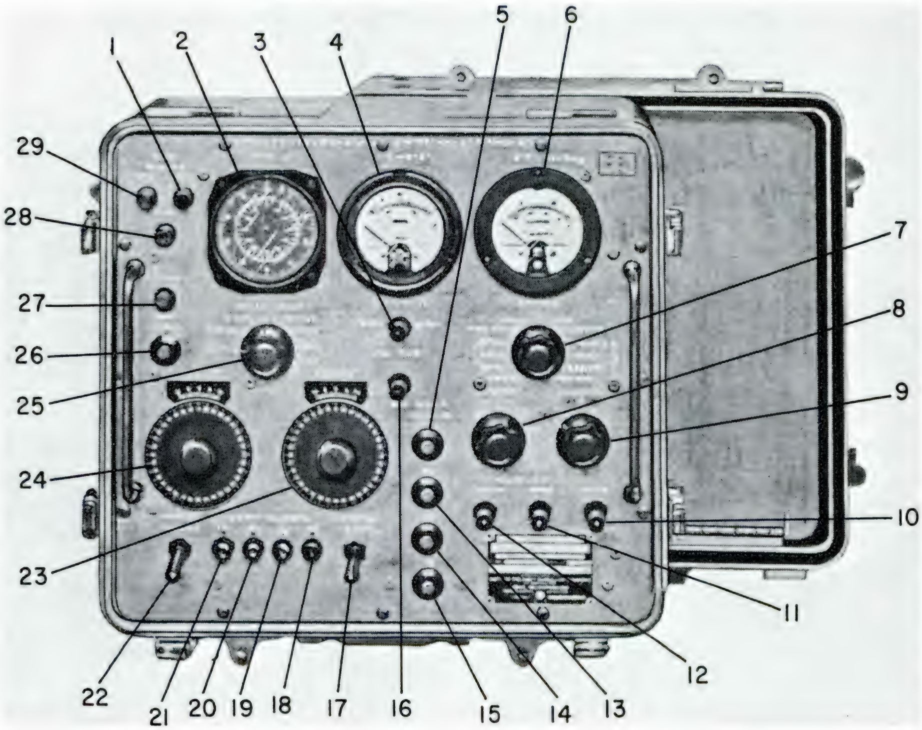
The AN/ASN-37 Attitude Heading Reference System Analyzer (fig. 14-23) provides a means of checking the operation of the AN/ASN-37 Attitude Heading Reference System without removal of system components from the aircraft. It provides the signals, indicating devices, and switching functions required. The analyzer is portable and is capable of being hand carried. Power requirement for operation of the analyzer requires 400 Hz, 3-phase (wye neutral ground) 115/200-volt a.c. Phase sequence is A to B to C. Also 27.5 d.c. is required.

All operating controls are located on the front panel assembly of the analyzer and are shown in figure 14-23. The function of each control is listed in table 14-1.

For detailed theory of operation of the analyzer refer to the applicable manual.

ANALYZER COMPUTER SET (AN/AJB-3) LT 3276

The analyzer computer set (fig. 14-24) is designed to check the operational performance of the Computer Set, Loft Bomb Release, Type AN/AJB-3 without removal of system components from the aircraft. It provides the



AE.717
Figure 14-23.—AN/ASN-37 Attitude Heading Reference System Analyzer.

switches, meters, and indicating lights necessary for monitoring the input, output, and excitation voltages of the computer set. It also provides simulated signal inputs necessary for all-attitude indication and bombing function checks.

The analyzer is portable and can be hand-carried. Power requirements for operation of the analyzer require 27.5-volts d.c. and 115-volts a.c., 400 Hz, 3-phase 4 wire wye connected neutral grounded with ABC phase rotation.

All operating and adjustment controls are located on the front panel of the analyzer and the function of each control is listed in table 14-2.

For detailed theory of operation of the AN/AJB-3 computer set analyzer refer to NA 17-15FB-501.

ELECTRICAL POWER TEST SET AN/PSM-20A

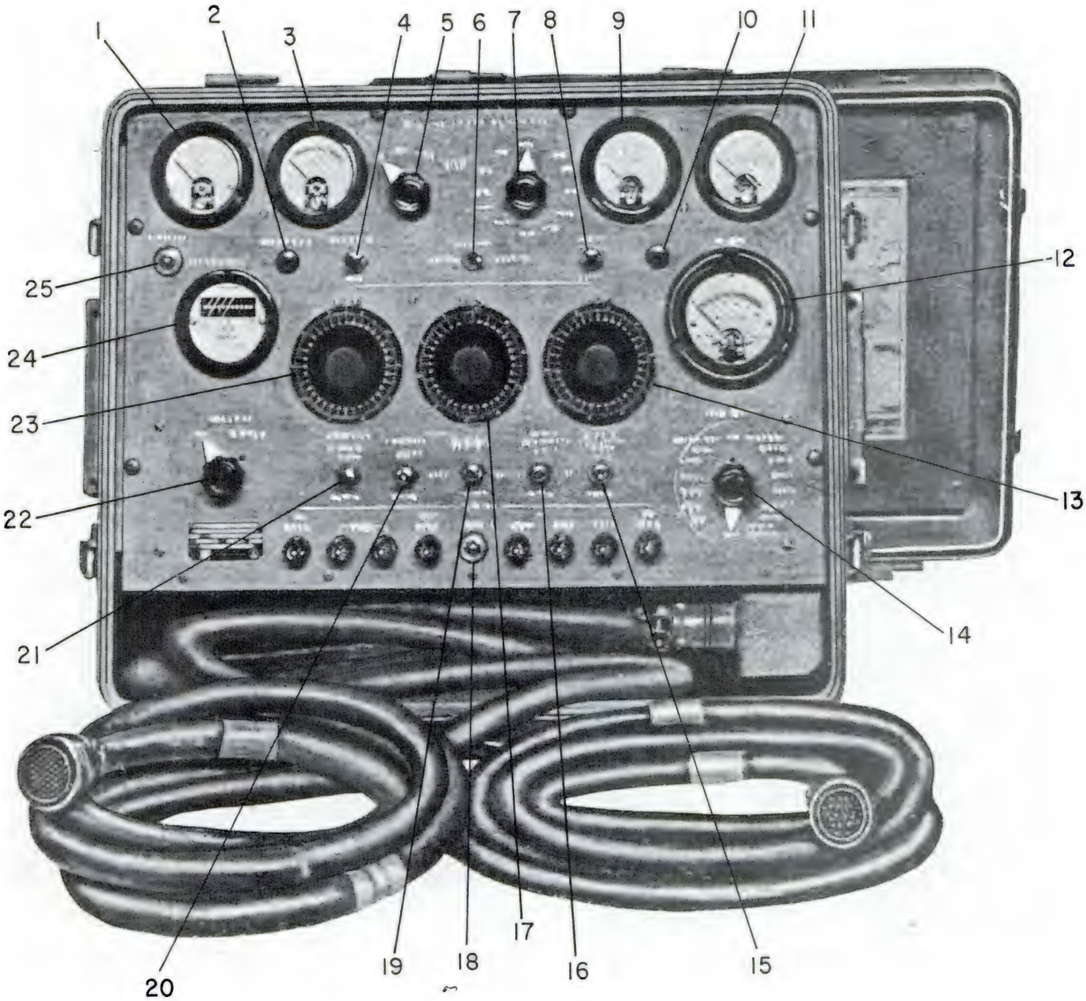
This test set is designed to be used on the F-4B aircraft during flight line checkout and troubleshooting of the aircraft electrical generating and distribution system. The test set is capable of measuring the voltage, frequency, watts, VARS, phase sequence and phase relationship of the aircraft's generators, and monitoring the aircraft's electrical regulation and distribution circuits. Faulty circuits or components are identified by comparing the test set indicators with known values.

The test set (fig. 14-25) is contained in a metal case and has a removable cover which provides protection and storage for interconnecting cables. Place cards containing instructions for maintenance and a schematic diagram of the test set are attached to the cover.

The control panel consists of two kilowatt-kilovar meters, one a-c voltmeter, one frequency meter, and one d-c voltmeter. Six indicator lights are provided on the panel to monitor generator phase sequence, generator synchronization, and aircraft electrical control circuitry. Switches are provided to select various circuits to be monitored by the test set

Table 14-1.—Analyzer operating controls and indicators.

No. in fig. 14-23	Description	Control (Marked)	Use
1	Lamp	PHASE SEQUENCE CBA	During start cycle.
2	Indicator	SYNCHRO	During various tests.
3	Switch	ROLL PRECESS	During erection rate test.
4	Meter	DC VOLTAGE	During all tests.
5	Switch	ϕA POWER INTERRUPT	During power failure warning test.
6	Meter	AC VOLTAGE-CURRENT	During all tests.
7	Switch	AC SELECT	During all tests.
8	Control	RANGE	During all tests.
9	Switch	CURRENT	During power consumption test.
10	Switch	LEVEL AMPLIFIER TEST	During amplifier tests.
11	Switch	PITCH AMPLIFIER TEST	During amplifier tests.
12	Switch	ROLL AMPLIFIER TEST	During amplifier tests.
13	Switch	ϕB POWER INTERRUPT	During power failure warning test.
14	Switch	ϕC POWER INTERRUPT	During power failure warning test.
15	Switch	DC POWER INTERRUPT	During synchronization tests.
16	Switch	PITCH PRECESS	During erection rate tests.
17	Switch	DIR GYRO	During all tests.
18	Circuit Breaker	DC CIRCUIT BREAKER	During all tests.
19	Circuit Breaker	ϕC CIRCUIT BREAKER	During all tests.
20	Circuit Breaker	ϕB CIRCUIT BREAKER	During all tests.
21	Circuit Breaker	ϕA CIRCUIT BREAKER	During all tests.
22	Switch	COMPASS	During all tests.
23	Control	DIR GYRO	During various tests.
24	Control	COMPASS	During slaved and compass azimuth system tests.
25	Switch	SYNCHRO SELECT	During various tests.
26	Switch	TURN CUTOUT	During roll erection test.
27	Lamp	ROLL ERECTION	During roll erection and switching rate gyroscope tests.
28	Lamp	FLAG	During start cycle and power failure warning tests.
29	Lamp	PHASE SEQUENCE ABC	During all tests.



AE.718

Figure 14-24.—Analyzer computer set (AN/AJB-3).

and to introduce faults into the aircraft circuits for the purpose of testing various aircraft protective devices.

The operation of the metering and switching functions is elementary and conventional and does not require explanation here. For a review of these meter types, refer to Basic Electricity, NavPers 10086-B.

VARIABLE ENGINE AIR DUCT RAMP CONTROL SYSTEM TESTER AN/PSM-19

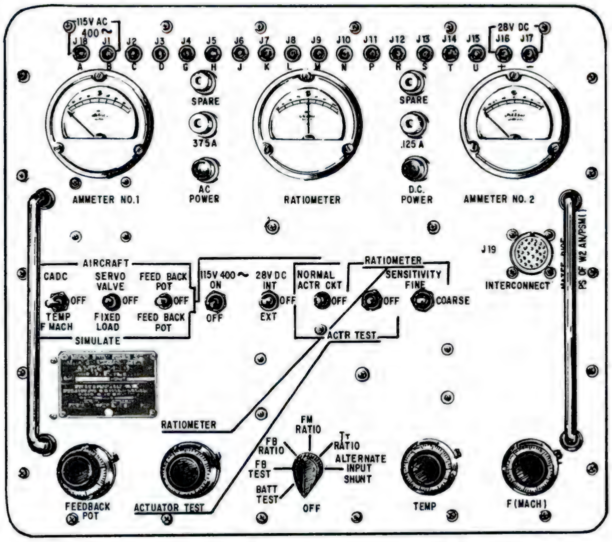
This tester is utilized during preflight, functional, and maintenance testing of variable engine air duct ramp control systems.

The tester (fig. 14-26) is a portable unit and consists of a plug-in panel housed in an aluminum carrying case. The lid is detachable and

Table 14-2.—Operating controls and indicators for the AN/AJB-3 analyzer.

No. in fig. 14-24	Description	Markings	Used during test of
1	Meter	AC VOLTS	System voltage tests.
2	Lamp	BOMB MODE	Bombing functions tests.
3	Meter	AC AMPS	System voltage tests.
4	Switch	ARMAMENT DC	Bombing functions tests.
5	Switch	POWER	System voltage tests.
6	Switch	FLUX VALVE	Azimuth system operational test.
7	Switch	FLUX VALVE SIMULATOR	Azimuth system operational test.
8	Switch	DC AMPS	System voltage tests.
9	Meter	DC AMPS	System voltage tests.
10	Lamp	READY	Gyroscope erection and azimuth system automatic synchronization.
11	Meter	DC VOLTS	System voltage tests.
12	Voltmeter	AC VTVM	System voltage tests.
13	Synchro transmitter	SIMULATE YAW	Indicator performance and bombing functions test.
14	Switch	VTVM SELECT	System voltage tests.
15	Switch	PLATFORM LEVEL AMPL	Platform amplifier tests.
16	Switch	PLATFORM ROLL AMPL	Platform amplifier tests.
17	Synchro transmitter	SIMULATE ROLL	Indicator performance and bombing functions tests.
18	Lamp	POWER	Gyroscope erection and azimuth system automatic synchronization.
19	Switch	PRECESS ROLL	Slow erection rate test.
20	Switch	PRECESS PITCH	Slow erection rate test.
21	Switch	PLATFORM PITCH AMPL	Pitch selector amplifier test.
22	Switch	DISPLACEMENT	All tests.
23	Synchro transmitter	SIMULATE PITCH	Indicator performance and bombing functions tests.
24	Meter	FREQUENCY	System voltage tests.
25	Lamp	PHASE SEQUENCE	Gyroscope erection and azimuth system automatic synchronization.

AE.719
Figure 14-25.—Electrical power test set panel.



AE.720
Figure 14-26.—Ramp control system tester.

has provisions for cable and accessory storage. The lid also contains a schematic diagram as well as a switch position table.

The test set is designed to be inserted into the aircraft variable inlet duct ramp control system. It serves as an aid during installation and in the calibration of the system to the ramp position. It also serves as an aid in the calibration of the Central Air Data Computer (CADC) output. The test set is designed to be used as an aid in troubleshooting the aircraft variable inlet duct ramp system. Should a component failure occur, the test set can be used to locate the defective component. The test set is designed for insertion in series with the ramp control system amplifier and associated aircraft wiring.

The tester contains three instruments—a ratiometer and two ammeters. The ratiometer is used in conjunction with a dial switch to read the various outputs from the system under test. The ammeters monitor the differential current across the actuator servo valves to indicate the unbalanced condition necessary to cause actuator ram motion and to read the unbalanced current during a null condition of the system under test.

The rotary selector switch, located at the lower center portion of the panel, has seven positions including an OFF position. The function of this switch is to select various outputs from the aircraft inlet duct ramp control system so they may be read on the ratiometer. The positions are as follows:

1. The BAT TEST position checks the output current from the ratiometer by utilizing the self-contained 6-volt battery.
2. The FB TEST (feedback test) position is used to check the feedback potentiometer total resistance.
3. The FB RATIO (feedback ratio) position checks the feedback potentiometer ratio for any given variable inlet duct ramp position.
4. The F_M RATIO (F Mach ratio) position checks the F (Mach) potentiometer output from the aircraft's CADC system.
5. The T_T RATIO (temperature ratio) position is used to check the total temperature potentiometer output from the aircraft CADC.
6. The ALTERNATE INPUT SHUNT position checks the ramp control amplifier input shunt resistors.

The panel contains eight toggle switches which perform the following functions:

1. The CADC BRIDGE, TEMP F MACH—In the aircraft position, allows normal operation

of the CADC bridge for calibration of the system. In the simulate position, simulates temperature on F (Mach) inputs to the CADC.

2. SERVO VALVE, FIXED LOAD—In the aircraft position, allows normal operation of the ramp actuator servo valve for calibration of the system. In the simulate position, simulates servo-valve load for bench testing such as presetting of the system's amplifier prior to installation in the aircraft.

3. FEEDBACK POT—In the aircraft position, allows normal operation of the feedback potentiometer for calibration of the system. In the simulate position, simulates feedback potentiometer for bench test purposes.

4. The 115 V 400 HERTZ—Used to connect 115-volt, 400-Hz, single-phase power to the system during aircraft checks or calibration. It is also used to apply an external source of power for bench tests or presetting the system amplifier.

5. 28 VDC—Is used to select internal battery or external 28-volt d.c. when used.

6. NORMAL ACTR CKT, ACTR TEST—In the normal position, allows normal operation of the servo valve for ramp calibration. In the ACTR TEST position, checks actuator operation with a simulated CADC input to the servo valve to isolate any malfunction of the servo valve or actuator.

7. RATIOMETER, ACTR TEST—In the ratiometer position, selects the ratiometer readout of the system outputs. It is also used to operate the actuator when the NORMAL ACTR CKT, switch is in the ACTR TEST position, for isolating a malfunction of the actuator or servo valve.

8. RATIOMETER SENSITIVITY FINE, COARSE—In the COARSE position, keeps from pegging the ratiometer and makes the zero adjustment of the ratiometer. In the FINE position, it adjusts the ratiometer to the zero position for a more accurate reading.

Four dial type switches are also included and perform the following functions:

1. FEEDBACK POT—Is used to simulate the aircraft feedback potentiometer for bench testing of the system's amplifier.

2. RATIOMETER ACTR TEST—Used in conjunction with the ratiometer to read the aircraft's outputs in resistance ratio or to operate the actuators separately to isolate a malfunction.

3. TEMP—Used to simulate temperature outputs from the CADC bridge for calibration or to simulate temperature input signals to the amplifier for bench testing or presetting.

4. F (MACH)—Used to simulate F (Mach) outputs from the aircraft's CADC bridge for calibration or to simulate F (Mach) input signals to the amplifier during bench testing or presetting.

For more specific testing of any component of the variable inlet duct ramp system, consult the applicable Maintenance Instructions Manual. For detailed use of the tester, refer to the current Operation and Service Instruction Manual, NA 17-15A-21.

PNEUMATIC PRESSURE TEST SET AN/PSM-15

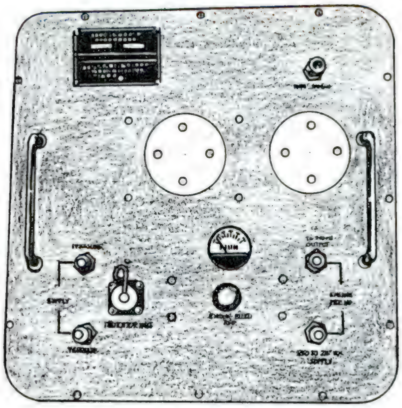
This device is a portable, self-contained pressure and vacuum test set whose primary function is the accurate simulation of pitot and static pressures. These pressures may be utilized to test an aircraft pitot-static system, or any components which derive outputs from the pitot-static system such as the flight control system.

The pressure simulator unit, shown in (A) of figure 14-27, contains a pressure-vacuum pump, a gage, and a regulator. The regulator is used to control an auxiliary air supply if desired. The necessary hose and connecting cables are stored in the lid of this unit.

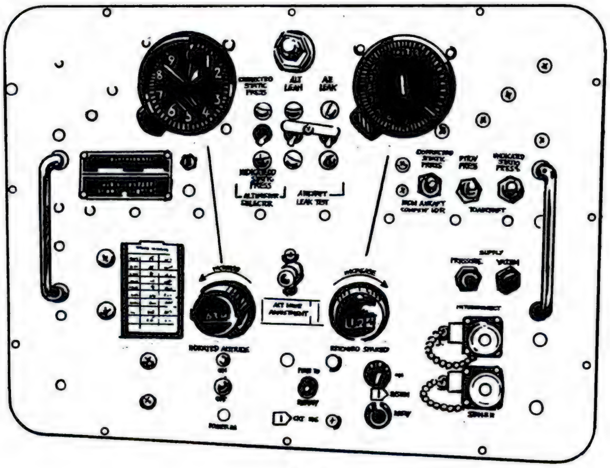
The control indicator unit (fig. 14-27 (B)) contains all the remaining indicators and controls. These indicators are the altimeter and the airspeed and Mach number indicator. The controls provided are the indicated airspeed control, indicated altitude control, and the altitude rate adjustment. The unit also contains the indicator lamps and a power switch.

A logging card is installed in the control indicator unit lid so that the operator may record control indications of often used test points for possible future use.

Automatic venting provisions are included in the test set which prevent negative impact pressures or large pressure transients from being applied to the equipment under test during shutdown of the test set. This feature permits the operator to leave the controls set at a test point and to turn the equipment off if the test is interrupted. The unit may be turned back on without repositioning the controls, and the test completed with no damage to the test set or the equipment under test.



(A)



(B)

AE.721

Figure 14-27.—Pneumatic pressure test set; (A) Pneumatic pressure simulator; (B) control indicator unit.

For detailed instructions on the use of this test set refer to the current Operation and Service Instruction Manual, NW 17-15GD-1, or the Maintenance Instructions Manual of the aircraft.

AIR-CONDITIONING TEST SET AN/PSM-21

The Air-conditioning Test Set AN/PSM-21 (fig. 14-28) is designed for functional testing and troubleshooting electrical components of the cabin and pressure suit, air-conditioning system, and the equipment air-conditioning system installed in the F-4B aircraft.

AE.722

Figure 14-28.—Air-conditioning system test set.

The power required for operation of the test set is obtained from the aircraft's electrical system. Simulator potentiometers are incorporated in the test set to simulate resistances of limiter sensor temperature probes. Changing the simulated resistance values controls the operation of various components of the air-conditioning system. Indications of the output functions of the temperature control amplifier can be monitored by indicator lamps on the test set. Test points on the test set provide a means of monitoring the resistance of sensor and limiter temperature probes installed in the aircraft and the simulator potentiometers in the test set. Switches on the tester are used to select the mode of operation. Aircraft power lamps on the test set are used to indicate that power is being supplied to the air-conditioning system being tested.

The test set is built into a suitcase type container. The base of the container houses the control panel on which switches are mounted for circuit selection, potentiometers to simulate and induce temperature changes, indicator lights

to show when and what circuits are being energized, and tip jacks through which various resistance readings are obtained. The lid contains the test set operating instructions, wiring schematic, and the storage compartment for the cable assemblies.

Detailed operating instructions for using the tester and troubleshooting the system can be found in the current Operation and Service Instruction Manual, NA 17-15BH-6, for the tester and/or the Maintenance Instructions Manual for the aircraft being serviced.

C-8 COMPASS BENCH TEST SET

The primary function of this test set is to determine if the individual components of the compass system satisfy their performance requirements. The secondary function of the test set is to facilitate the repair of malfunctioning compass system components by isolating defective circuit elements using a systematic procedure of continuity and circuit current testing.

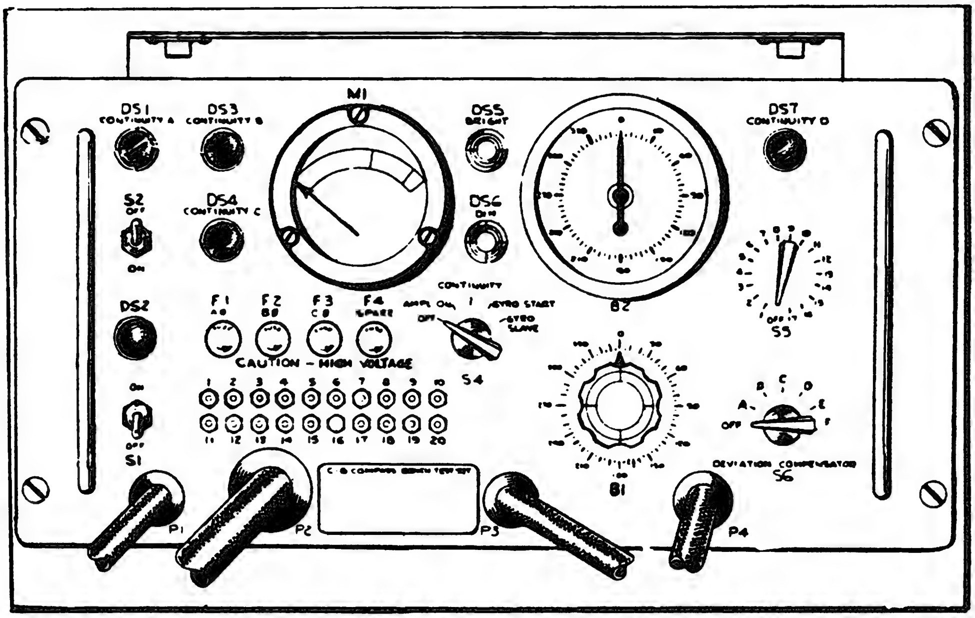
The compass test set is a completely self-contained unit designed to provide a means of GO, NO-GO testing of the components of the system either separately or all together. The test set, when correctly calibrated and connected to the compass system, provides a means of:

1. Connecting the test set microammeter in series with various compass system component circuits to measure current flow.
2. Applying voltages of proper magnitude and frequency to the compass system component circuits.
3. Checking continuity of each component of the compass system.
4. Adjusting the flow of current to a predetermined standard value range in individual component circuits when required.

The test panel is shown in figure 14-29.

The test set may be operated to apply voltages of known magnitude and frequency to selected component circuits and measure the circuit current. During the tests performed on any one component, the test set also substitutes for the circuit elements normally supplied by related (electrically connected) components. Continuity of the circuits in each component is thereby maintained through the circuits of the test set, making it possible, therefore, for the test set to test any compass system component without references to any other component.

The value of the current flowing in each circuit is then compared, using GO, NO-GO bands of the scale of the microammeter on the test set panel, with the current value established for



AE.723

Figure 14-29.—C-8 compass bench test set panel.

that circuit as a requirement for satisfactory performance of the compass system in an aircraft.

To facilitate comparison of the current values in the compass system component circuits with required values, the test set adjusts (limits) the current value in component circuits as required so that only one "standard," or GO, current value range is required for comparing current flow in all component circuits. This adjustment of current flow is accomplished by manipulation of a rotary switch on the test set panel which operates to insert resistances of appropriate values in series with the circuits of the compass system components.

For complete instruction on this tester, refer to the current Operation and Service Instruction Manual, NW 17-15CA-18, or the aircraft's Maintenance Instruction Manual.

MAGNETIC COMPASS CALIBRATION TEST SET (MC-2)

The magnetic compass test set (fig. 14-30) provides a controlled and simulated magnetic field about the aircraft's transmitter to calibrate accurately the magnetic compass system

AE.724

Figure 14-30.—MC-2 compass calibrator test set.

of the aircraft. The test set has the capability of determining compass system errors without rotation of the aircraft to various headings as on a compass rose. The compass calibrator also has the capability of surveying an area for the layout and markings of a compass swing site. The compass calibrator provides electrical heading inputs from 0° to 345° in 15° increments with an accuracy of 0.1°.

To swing the compass requires that an aircraft be towed into position along the north-south line and requires that the compass transmitter be removed from the aircraft.

For detailed theory of operation and maintenance of the MC-2 tester, refer to the Operation and Service Instruction Manual, NA 17-15CAA-45.

SYNCHROPHASER TEST SET

This test set (fig. 14-31) is designed to test propeller synchrophaser electronic units. The test set generates all the pulses (d.c. and a.c.) required to functionally test the synchrophaser electronic unit completely independent of all its associated components.

AE.725
Figure 14-31.—Synchrophaser test set.

The test set is completely transistorized. Its multicircuit switches are specially designed for simplicity of operation. Each switch position programs a particular test by connecting the appropriate inputs to the synchrophaser and the necessary meter required to verify the synchrophaser performance for the particular test.

The test set generates a master pulse and a slave pulse. The pulse circuits are designed to closely simulate the synchrophaser pulse input under the dynamic flight conditions. Different phase and speed relationships of the master and slave pulses in accordance with synchrophaser test specifications are programed by setting one of the selector switches for a particular test.

The output of synchrophaser associated components is simulated by the test set. It provides a simulated tachometer signal and the resistance of synchrophaser controls for certain tests. When programed by the selector switches, these signals facilitate measurement of the synchrophaser dynamic response to off-speed, off-phase, speed reset, resynch, and throttle anticipation signals.

Control adjustments are minimized. Only a few of the automatically programed tests require adjustment of either the feedback gain potentiometers. The accuracy of control adjustment is optimized by designing the test set circuits such that the few adjustments required are null or zero settings on center scale zero meters.

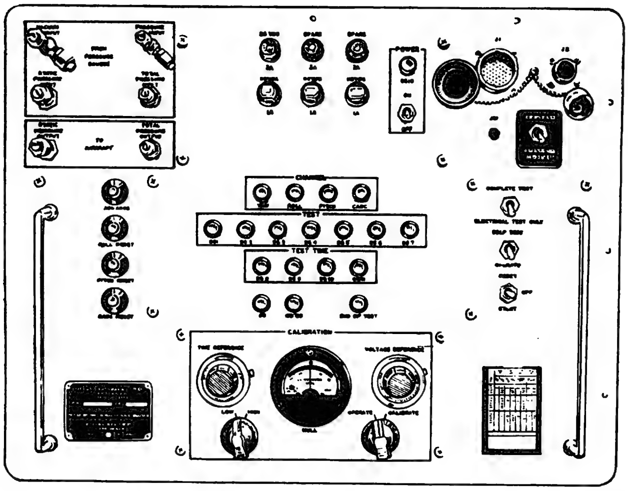
A high degree of accuracy and repeatability is a feature of the gain measuring circuits within the tester. Conventional gain circuits require application and measurement of incremental voltages to the synchrophaser for comparison with resultant output voltages. The gain measurement circuit employs a galvanometer, demodulator, d -c power supply, and calibrated potentiometer in a bridge circuit. When the gain test is programed by setting the appropriate selector switch, the calibrated potentiometer is rotated to null the galvanometer; with the galvanometer nulled, the potentiometer calibration gives a direct readout of amplifier gain. This circuit avoids the inaccuracies of input settings and error amplification of incremental gain comparison and the possibility of error in calculating the gain factor.

For complete instructions on this tester refer to the current Operation and Service Instruction Manual, NW 17-15D-3.

AUTOMATIC PILOT TEST SET AN/ASM-49

This test set (fig. 14-32) is used for testing the Flight Control Group AN/ASA-32, and provides the following dynamic response tests for this flight control group:

1. Proper response time.
2. Backlash in overall system rigging.
3. System gain.



AE.726

Figure 14-32.—Automatic Pilot Test Set AN/ASM-49.

The tester is capable of making a pneumatic step function check of the Mach and altitude hold signals supplied by the aircraft's air data system. This is accomplished by using the test set, in conjunction with a suitable pitot-static source, to apply a pneumatic step function while monitoring the resulting reaction. However, if a pneumatic step function check is not desired, an electrical test may be used.

The test set performs a complete dynamic test of the pitch, roll, and yaw channels of the flight control system by simulating the electrical signals from the respective sensors including those of the Mach and altitude hold functions.

The test set is portable with a hinged cover which provides storage for the synchro assemblies and connecting cables. Power requirements for the operation of the dynamic test set are 28 volts d.c. and 200/115 volts, 3-phase, 400 Hz. The dynamic test set receives its power requirements from the aircraft through cable assemblies.

Complete step-by-step procedures for making the dynamic test as well as the detailed theory of operation of the test set may be found in the current Operation and Service Instruction Manual, NA 17-15KK-3.

FLIGHT CONTROL TEST BENCH AN/UJM-2

The flight control test bench (fig. 14-33) is a highly technical and complicated shop tester designed to test the flight control system installed in the A-5A.

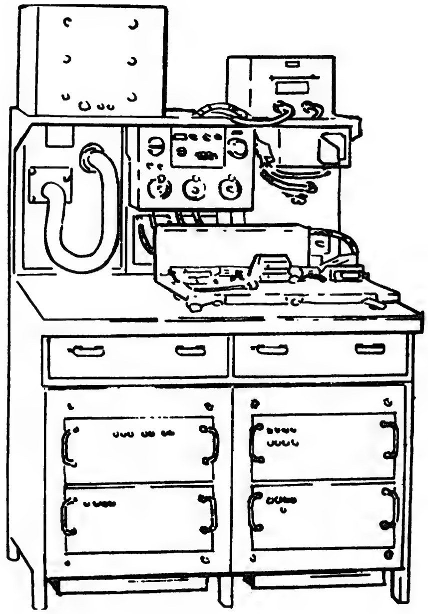


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Figure 14-33.—Flight Control test bench.

The flight control panel provides manually controlled synchro control transmitter outputs to simulate pitch, roll, and heading outputs for testing the automatic flight control system of an aircraft. A simulated Mach trim output is also provided for testing the longitudinal series servoamplifier. The flight control panel provides the switching arrangements for the application of a -c and d -c power from the flight control test bench cable harness to the flight control test bench components. The panel of

the test bench consists of three basic assemblies as follows:

1. A power distribution panel.
2. A control panel.
3. A radar altimeter indicator.

Radar altimeter simulations are indicated on the panel by a radar altimeter indicator. Complete instructions on the installation, use, and care of this test equipment can be obtained from the current Operation and Service Instruction Manual, NW 16-50BAA-2-3.

FLIGHT CONTROL TEST CONSOLE OA-3740/ASA-48

The AFCS test console (fig. 14-34) is used for semiautomatic and manual testing of airborne replaceable assemblies (ARA's) removed from the Automatic Flight Control System AN/ASW-16 and AN/ASW-15.

The AFCS test console is used in the performance of shop maintenance on malfunctioning ARA's of the AFCS. These ARA's are removed from the AFCS after being indicated

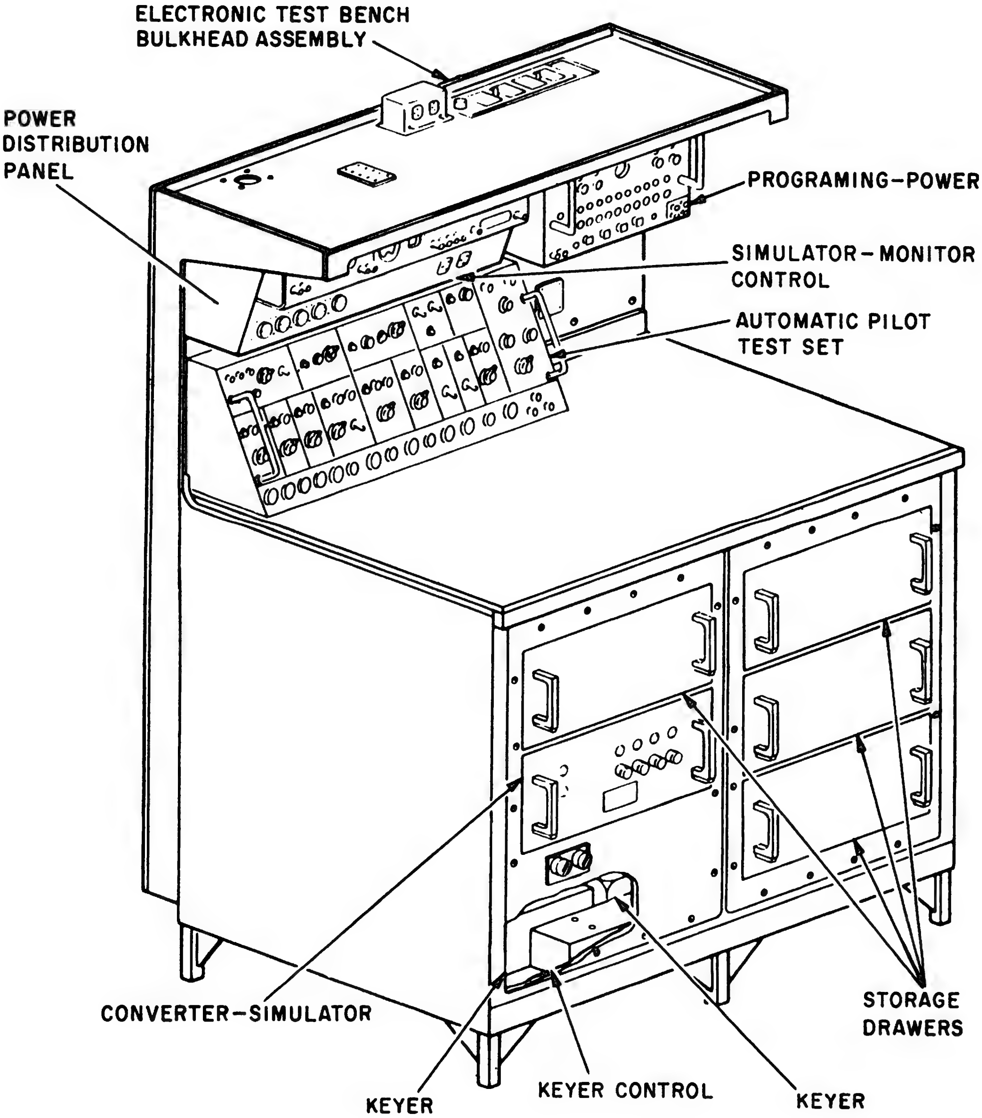


Figure 14-34.—Flight Control Test Console OA-3740/ASA-48.

as the causes of malfunctions occurring during in-flight, flight-line, or hangar testing. At the shop (shore-based or carrier-based), the AFCS test console is connected to the malfunctioning ARA and, when semiautomatic procedures are to be performed, to the programing test console. The AFCS test console is then used to further localize the malfunction to the defective part within the ARA.

When localizing a malfunction to a defective part or assembly containing the defective part, the AFCS test console, responding to automatically sequenced test programs, selects specific circuits in the malfunctioning ARA. These circuits are tested by being stimulated in a prescribed manner. The responses that result from this stimulation are then evaluated. The test program, coded on prepunched tapes which are installed in the programing test console, simulates the normal inputs to the ARA; the ARA generates its normal output. Each test program must be initiated (and restarted after a stoppage) manually. Once started, the test program proceeds automatically until completed or halted by a malfunction or by a manual or pre-programed command; thus the operation is semiautomatic rather than automatic. If a stoppage is caused by a malfunction, the AFCS test console is automatically programed through a self-test to check the reliability of the console. If it passes this self-test, instructions are provided in an operator's checklist for repairing the malfunctioning ARA.

NOTE: Air navigation computers for the ASW-15 and ASW-16 are the only AFCS ARA's for which the semiautomatic phase of malfunction isolation is employed; malfunctions in the other items to be tested can be isolated using manual programing and troubleshooting techniques.

When localizing a malfunction to the defective part within an assembly, it is necessary at times to manually program the AFCS test console from controls within the test console. By means of these controls, any step that is punched on the test tape can be selected at any time and the response of the ARA assembly. displayed on auxiliary test equipment for as long as required. The defective part is isolated using the displayed responses and troubleshooting techniques. Complete operating and test procedures for the test console are contained in the Operation and Service Instruction Manual, NA 16-50BAB-2-4.

INERTIAL NAVIGATION TEST CONSOLE (OA-3742/ASA-48)

The INS test console (fig. 14-35) is used for semiautomatic and manual-step testing of ARA's (aircraft replaceable assemblies) removed from Inertial Navigation System AN/ASN-31 or AN/ASN-36 for maintenance. These ARA's are listed in table 14-3.

The INS test console is used to perform shop maintenance of a malfunctioning ARA removed from either the AN/ASN-31 or AN/ASN-36 INS equipment. Defects in the performance of an ARA are detected during operation, or during flight-line or hangar testing. As a result, the malfunctioning ARA is removed from the aircraft and sent to a shore- or carrier-based shop.

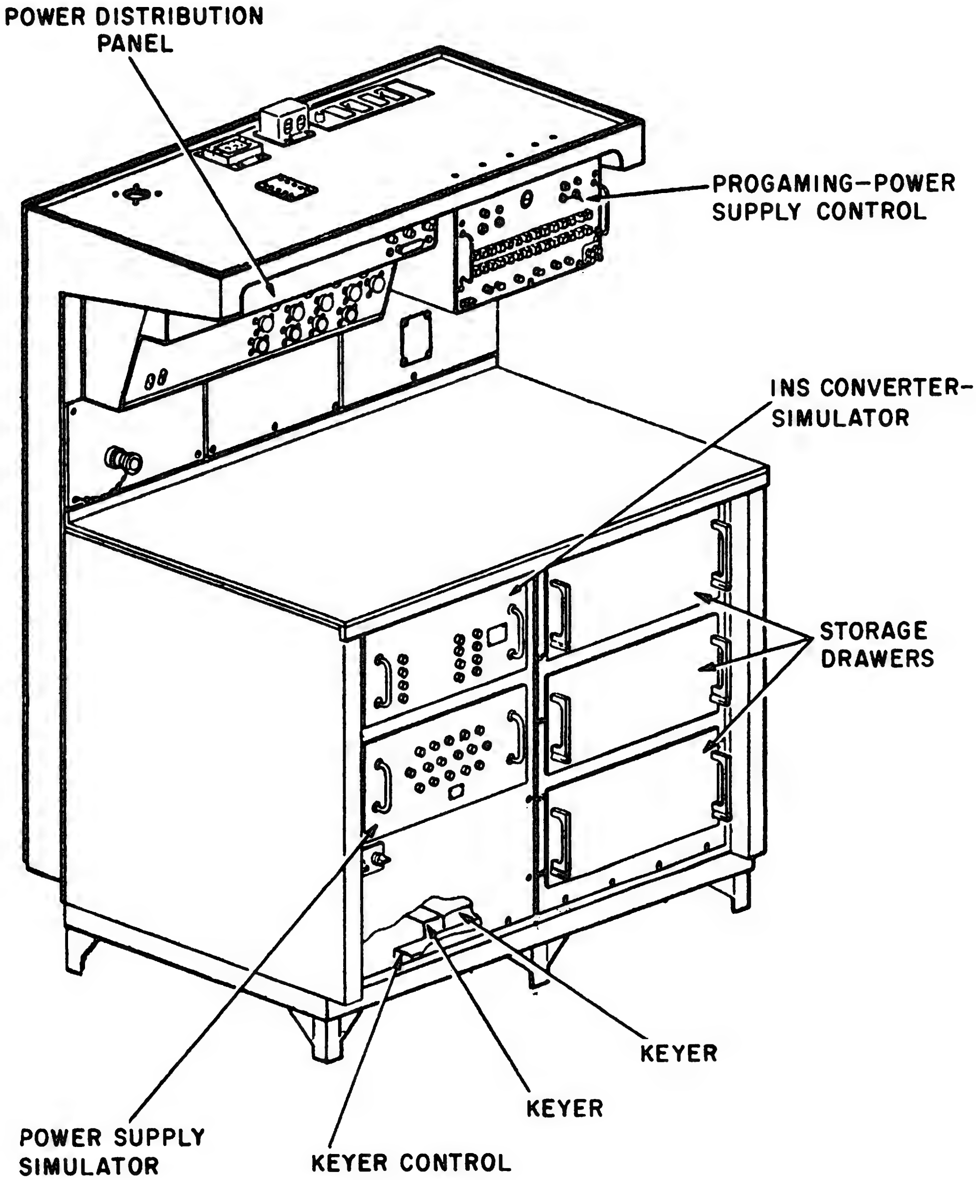
In the shop, the ARA is electrically connected to the INS test console, which is used in conjunction with the programing test console to localize the malfunction. The INS and programing test consoles are part of the avionics test set. The avionics test set is an integrated shop test system which is capable of semiautomatically isolating a malfunction within an ARA to a module. This semiautomatic testing is accomplished by use of test programs coded on punched tapes. The programing test console uses decoded tape commands to generate command signals which cause analog and control circuits in the INS test console to operate. This operation produces signals which simulate normal inputs to the ARA. The resulting ARA outputs are processed by the INS test console and returned to the programing test console for evaluation.

After a malfunction has been localized to a module by a semiautomatic tape program, auxiliary test equipment and manual troubleshooting techniques and/or manual test programs using the INS test console are employed to further isolate the malfunction to a faulty part within the module. Programed self-test routines check the reliability of the INS test console prior to tests on the INS ARA's.

For detailed operating instructions and maintenance of the INS test console refer to the Operation and Service Instruction Manual, NA 16-50BAB-2-7.

ENGINE ANALYZERS

The development of new equipment to assist the Aviation Electrician's Mate in troubleshooting the engine ignition system was comparatively



AE.729

Figure 14-35.—INS test console.

slow prior to the advent of the engine analyzer. Other methods permitted troubleshooting on the ground only. The airborne engine analyzer removed this restriction. In-flight troubles can now be logged and the Aviation Electrician's Mate can start correcting the discrepancies as soon as the flight is completed, thus saving a lot of time that was previously used in locating the troubles after a flight. The same features of airborne analyzers are available to the Aviation Electrician's Mate on the ground. As a ground device, the analyzer can be attached to an aircraft engine in approximately 30 minutes.

The complete ignition system, from the ignition switch in the cockpit to the spark plugs, can now be checked quickly. In addition to the man-hours saved; the analyzer makes possible

Table 14-3.—INS ARA's to be tested using INS test console.

Nomenclature	Common name
Navigational Computer ASN-31	Platform computer
Electronic Control Amplifier ASN-31	Platform amplifier
Signal Data Converter ASN-31	Platform adapter
Signal Data Converter ASN-36	Platform adapter
Gyroscope Assembly Control ASN-31	Erection controller
Gyroscope Assembly Control ASN-36	Inertial control
Power Supply ASN-31	Power Supply
Control-Indicator	Doppler-platform control

a considerable saving of material. Some difficulties which are encountered only during flight and at relatively high altitudes are intermittent and cannot be reproduced during ground operation. Without the advantage provided by an analyzer in these cases, maintenance personnel cannot be sure that a trouble has been completely eliminated, and components of the ignition system are often replaced unnecessarily in an attempt to correct a discrepancy.

The analyzer can also be used to promote efficient preventive maintenance of the ignition system. Many ignition troubles do not develop suddenly. They begin as a malfunction that cannot be immediately detected and will become progressively worse unless the analyzer is used in the early stage to detect the malfunction. By using the analyzer on postflight and routine checks, it is possible to discover these otherwise unapparent discrepancies and replace the faulty components.

The analyzer is important from a safety point of view. In a few cases engine instruments may predict an engine failure; however, in most instances the failure has already occurred by the time the instruments indicate it. By using the analyzer, a check on all the ignition system components can be maintained. By using vibration analysis, the mechanical operation of the engine can be observed; however, most installations are not equipped for complete vibration analysis. With the information derived from the analyzer, the prediction of engine failure is received well in advance of the actual failure.

FUNCTIONS OF ENGINE ANALYZERS

Ignition Analysis

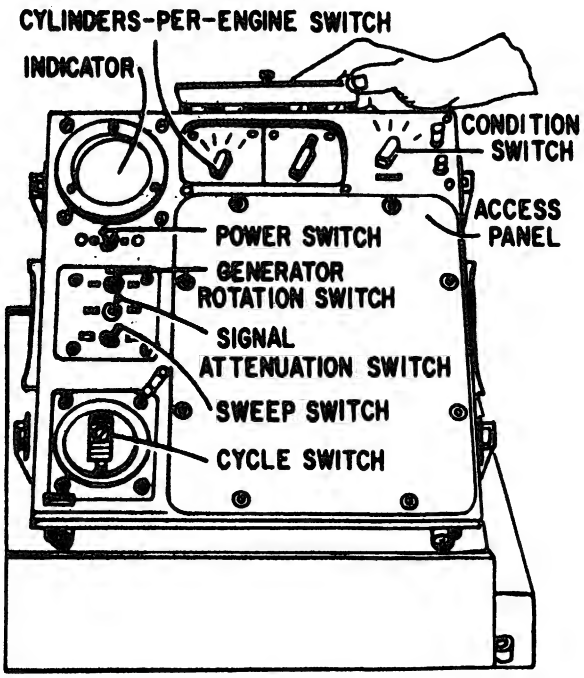
During ignition analysis, the engine analyzer records the voltage of the primary coil. In a sense the analyzer is a recording voltmeter, showing every change in voltage that occurs in the primary coil as the magneto completes a full cycle (two crankshaft revolutions). By sensing every change in the voltage of the primary coil, the analyzer shows how the magneto is operating. It shows breaker point operation and measures the length of time they are open. It indicates an improperly operating primary capacitor and shows the condition of the secondary circuit. To some extent the condition of the spark plugs will reveal to the experienced operator the condition of the cylinders.

Vibration Analysis

Vibration analysis is accomplished by installing vibration pickup units on the cylinders and connecting the units to the analyzer. These units convert vibrations into voltages which can be seen on the indicator of the analyzer. The use of vibration analysis can minimize the more costly engine repairs, such as cylinder changes and engine changes. By inspection of valve action and combustion characteristics the Aviation Electrician's Mate can see evidence of malfunctions before serious damage is done.

SPERRY PORTABLE ENGINE ANALYZER

The Sperry Portable Engine Analyzer can be used to analyze only one engine at a time. It is universal in that it can be used with any type engine. It can be used with engines having 7, 9, 14, 18, or 28 cylinders. The portable analyzer consists of an indicator, cycle switch, condition switch, power switch, signal switch for pattern attenuation, sweep switch, generator rotation switch, power supply amplifier, inverter, and isolating resistor, mounted in a single cabinet. A synchronizing generator, a vibration pickup unit, and connecting wires and cables complete the portable engine analyzer. A Sperry Portable Engine Analyzer is shown in figure 14-36.



AE.730

Figure 14-36.—Sperry, Portable Engine Analyzer.

Components

The basic components of the Sperry Portable Engine Analyzer are discussed in the following paragraphs.

The CATHODE-RAY TUBE (CRT) has a phosphorescent screen upon which voltages of the ignition primary circuit or of the vibration pickup units are displayed as patterns, which the operator interprets. An electron gun in the cathode-ray tube generates an electron beam and directs it against the screen. Two sets of deflection plates in the cathode-ray tube cause this beam to move on the face of the screen. Voltages in the primary circuit of the magneto (or vibration pickup units during vibration analysis) control the vertical deflection or movement. Voltages from the synchronizing generator control the horizontal deflection of the beam, according to crankshaft position. Changes in these voltages cause the position, shape, and size of the pattern to vary.

After considerable time in use, the face of the CRT may be etched with a horizontal line. The advantage of having a high intensity trace increases this possibility, due to the high-velocity electron bombardment of the tube screen material. Since the horizontal sweep is a baseline, 90 percent of the electron bombardment is always on it while the actual presentation of patterns represents a small percentage. The varying position and amplitude of ignition and vibratory patterns preclude any possibility of etching above or below the sweep baseline.

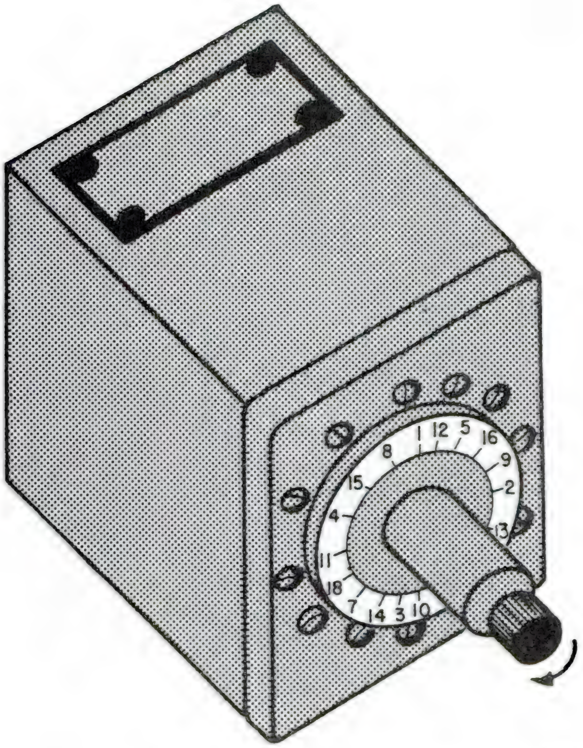
The CYCLE SWITCH (fig. 14-37) enables the operator to select the pattern of a certain position of the crankshaft (the pattern of a certain cylinder). Three removable faceplates, with the firing order of 9- and 18-, 7- and 14-, and 28-cylinder engines, are furnished with the Sperry Portable Engine Analyzer. A red dot at the base of the pointer of the cycle switch is used as an index mark for vibration analysis. When the red dot is alined with a selected cylinder number, the exhaust valve closing of that cylinder will appear on the left of the viewing screen.

A CONDITION SWITCH permits the operator to select the type of analysis desired. One is shown in figure 14-38. The condition switch has one index mark which may be lined up with one of five positions:

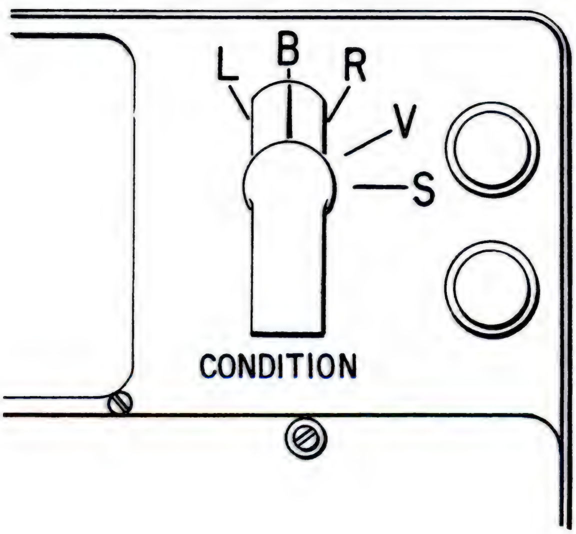
L—The pattern of the left magneto is shown on the indicator.

B—The pattern of both magnetos is shown on the indicator.

R—The pattern of the right magneto is shown on the indicator.



AE.731
Figure 14-37.--Cycle switch (with 18-cylinder faceplate installed).



AE.732
Figure 14-38.--Condition switch (portable).

V--The vibration pattern is shown on the indicator.

S--This position establishes the circuit for analysis of any other chosen source of signal voltage delivered to the analyzer by means of the two posts adjacent to the condition switch.

The POWER SWITCH is a two-position, ON-OFF toggle switch which controls the power to the analyzer.

The GENERATOR ROTATION SWITCH is a two-position switch, clockwise and counter-clockwise, which is provided to reverse the phasing sequence of the synchronizing generator. This feature permits the use of one cable for generators of either clockwise or counterclockwise rotation.

NOTE: The generator rotation switch must be placed in the position which causes the patterns to move from right to left when the cycle switch is rotated in a clockwise direction. The check for this condition is called the phasing check.

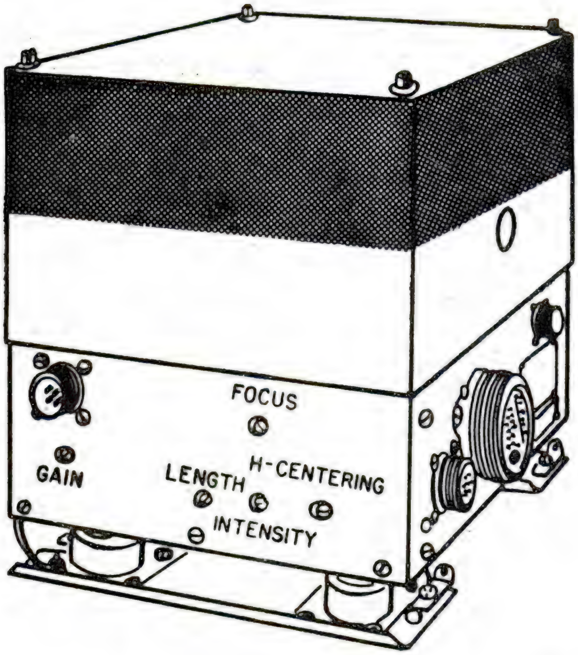
The SIGNAL SWITCH is a two-position switch, attenuated and normal. When this switch is in the NORMAL position, the patterns are of a normal size. In the ATTENUATED position, the signal voltages are reduced to a lower amplitude, and the patterns appear much smaller.

The SWEEP SWITCH is a two-position toggle switch, slow and fast. In the SLOW SWEEP position, the patterns for 720° of crankshaft travel (18 patterns on 18-cylinder engines) appear on the screen. In the FAST SWEEP position, the patterns for 80° of crankshaft travel (2 patterns on 18-cylinder engines) appear on the screen.

The POWER SUPPLY AMPLIFIER contains the various circuits, capacitors, transformers, and resistors necessary to provide the voltages required for the proper operation of the engine analyzer. It also provides the means of making the proper pattern adjustments. These are screwdriver adjustments. (See fig. 14-39.)

1. The intensity adjustment screw regulates the brightness of the pattern. The adjustment screw is turned in one direction or the other until the brilliance desired by the operator is obtained.

2. The focus adjustment screw controls the sharpness of the picture. The desired sharpness is obtained by turning the screw in one direction or the other.



AE.733
Figure 14-39.—Power supply amplifier showing screwdriver adjustments.

3. The H-centering (horizontal centering) adjustment controls the start of the trace line from the left side of the CRT. (The trace line, seen on the indicator, is caused by the electron beam being deflected across the CRT by the horizontal deflection plates.) The trace line is adjusted to begin 1/8 inch from the left side of the CRT. Before making the adjustment, the sweep switch must be in the SLOW SWEEP position, showing the patterns of all the cylinders.

4. The length adjustment controls the length of the trace line. It should be adjusted to give a trace line 2 1/2 inches long. This will normally extend the right end of the trace line to 1/8 inch from the right edge of the cathode-ray tube. The sweep switch must be in the SLOW SWEEP position for this adjustment also.

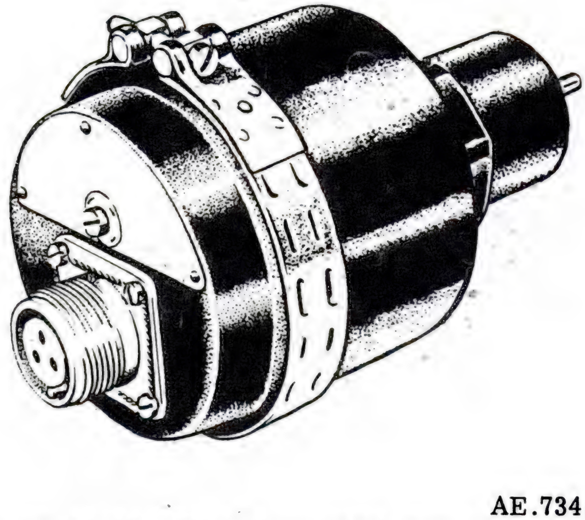
5. The gain adjustment is used only for vibration and special analysis. It controls the amplitude of the vibration patterns. It is adjusted to obtain vibration patterns of a size desired by the operator.

ISOLATING RESISTORS are in the circuit between the aircraft engine and the engine analyzer. They prevent the engine magnetos from grounding out in the event that the engine analyzer develops an unintentional ground.

The SYNCHRONIZING GENERATOR is mounted on the auxiliary tachometer drive of the aircraft engine. This is the unit that permits timing of the analyzer to the aircraft engine. It furnishes the voltages required for the horizontal deflection of the beam of electrons. Two types are available to fit either of two standard types of mounts with which aircraft engines are equipped. Each of these two types may be fitted with either a straight or an offset electrical receptacle.

Figure 14-40 shows a synchronizing generator, mounted by internal threads of the generator housing and having a straight electrical receptacle. Flexible drive shafts are provided for some installations. However, when a flexible shaft is used, it is possible for undesirable whip action of the shaft to have an adverse effect upon the timing.

The VIBRATION PICKUP UNIT, containing a coil and a magnet, is mounted on the aircraft engine cylinder head to be analyzed. The unit is installed either directly in a tapped hole provided in the cylinder head or in an adapter mounted in the tapped hole, depending on the particular engine. Since the portable engine analyzer is not equipped with a vibration selector switch and harness, it is possible to analyze, for vibration, only one cylinder of an engine. Any vibrations (impact forces) in the cylinder are transmitted to the magnet in the



AE.734
Figure 14-40.—Thread-mounted synchronizing generator with a straight receptacle.

pickup, causing the magnetic field to strengthen or weaken, producing voltage. The value of this voltage depends upon the impact forces in the cylinder.

Connecting the Portable Analyzer to the Engine

The portable engine analyzer is usually mounted in a portable cart assembly, equipped with a power panel and various cables for connecting the analyzer to the engine. If it is impracticable to use the cart assembly at any time, the engine analyzer may be removed from it, and power from the aircraft inverter or other source supplying the required 115-volt, a-c power may be used. The inverter which normally converts the 28-volt input to 115 volts would remain with the cart assembly; thus, it is not used when the analyzer is removed from the cart assembly.

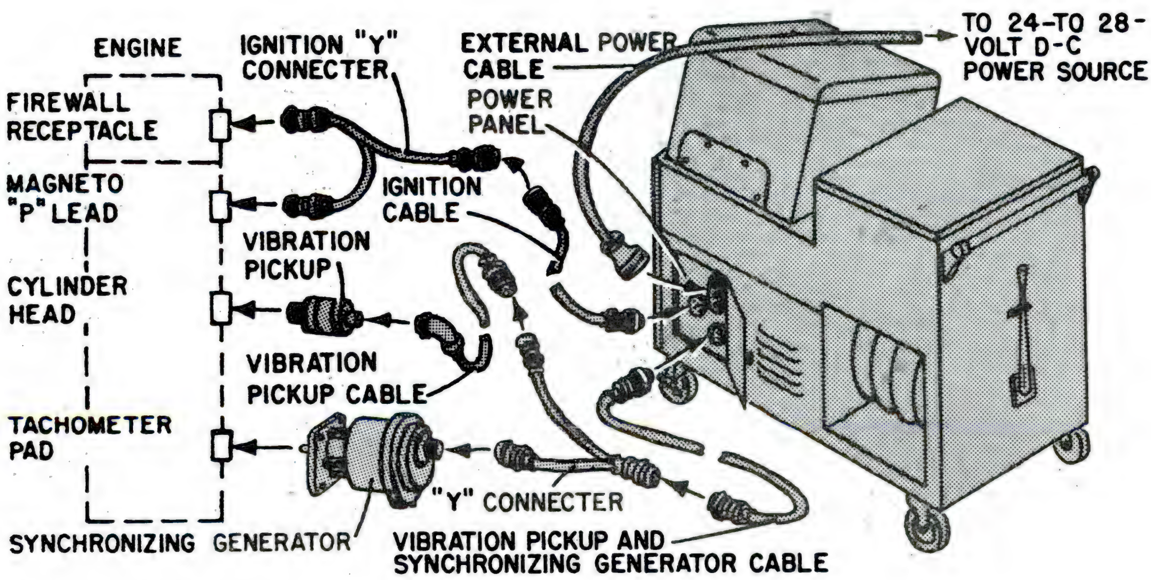
A general coverage of the procedure for connecting the analyzer to the engine is given here. The appropriate technical publication must be consulted for specific instructions. The general procedure is as follows:

1. Install the synchronizing generator on the auxiliary tachometer mounting pad, using the proper adapter, if necessary, and the appropriate generator type.
2. Install the vibration pickup unit on the cylinder head, if vibration analysis is desired.
3. Make the cable connections to the analyzer, as shown in figure 14-41.

Analyzer Malfunction

The responsibility for the maintenance of engine analyzers is assigned to the Aviation Electrician's Mate. Before attempting any form of maintenance on the analyzer, maintenance personnel should be thoroughly familiar with the basic principles and theory of operation of the equipment. A complete understanding of the equipment greatly reduces the time required to locate a malfunction.

When a malfunction occurs in the equipment, first check the obvious causes such as blown fuses, loose connections, etc. Next, check the tubes visually to see if each tube is lighted. If all tubes are operating properly, but the unit is still defective, check each of the test points with an oscilloscope for proper waveform. Finally, voltage and resistance checks should be taken on parts which seem defective. By following this procedure, minimum time is lost in locating the cause of malfunction.



AE.735

Figure 14-41.—Portable engine analyzer installation diagram.

CAUTION: If high voltage has recently been applied to the CRT, there may be energy stored in the tube. After being disconnected a few minutes, this energy may appear as a high-voltage charge on the high-voltage terminal of the tube and could discharge through the personnel during handling. To avoid this, the energy may be discharged through a short wire touched momentarily between the terminal and the outer surface of the CRT prior to handling.

For more detailed instructions on the maintenance of engine analyzers, refer to the appropriate Service Instruction Manual.

TEST EQUIPMENT MAINTENANCE

Some of the test equipments discussed in this chapter require special maintenance techniques. These have been mentioned as a part of the detailed coverage for the specific equipments to which they apply. In the following paragraphs a more general discussion of test equipment maintenance, applicable to most test equipments, is presented.

TYPES OF MAINTENANCE

Maintenance personnel must be prepared to repair and adjust certain types of test equipment should it fail in operation. The trouble must be located, and after repairs or replacements have been made, the equipment must be tested and adjusted to conform to the original system specifications. Maintenance personnel must endeavor to find the source of the trouble that causes equipment failure, particularly when the trouble is a recurrent one. The recurrence of a fault usually indicates that the effect, not the cause, has been remedied.

As with the other kinds of electronic equipment, the two basic types of maintenance for test equipment are preventive maintenance and corrective maintenance.

Preventive Maintenance

Preventive maintenance, as performed on the organizational maintenance level, is of major importance. Preventive maintenance is a systematic series of operations that can be performed on all electronic equipment at regular intervals. The purpose of this maintenance is to eliminate, whenever possible, major breakdowns and unwarranted interruptions in service. Through careful and conscientious efforts it is possible to keep this equipment operating at top efficiency at all times. By preventing breakdowns, valuable time can be saved at various levels of maintenance. The importance of this type of maintenance cannot be overemphasized. Electronic test equipment can only be utilized when the equipment is functioning normally and at maximum efficiency. It is vitally important that electronic maintenance men maintain this equipment properly.

These instructions have been compiled to serve as a guide for a properly organized approach to preventive maintenance. It is suggested that the general techniques outlined in the following paragraphs be utilized whenever possible.

FEEL.—The feel operation is utilized to check rotating machinery and parts that either radiate heat or normally vibrate. This is a check for overheating as well as for parts that are not working.

NOTE: It is important that the feel operation be performed as soon as possible after equipment shutdown. This operation is always performed before attempting any other maintenance work.

INSPECTION.—This is the most important operation in the preventive maintenance program. An untrained observer will have a tendency to overlook minor troubles. It is entirely possible that these troubles may not cause equipment failure at the time when they are first noticed, but after long hours of operation may be the cause of major breakdowns. The service technician should make every effort to become familiar with the complete operating system and the indications of normal functioning of the equipment.

Inspection of the equipment should consist of carefully observing all parts associated with the equipment, noticing their color, placement, state of cleanliness, etc. When performing this operation, look carefully for the following conditions:

1. Overheating. This is indicated by discoloration, blistering, or bulging of the parts. Leakage of chemical compounds from containers such as electrolytic capacitors gives warning of future breakdowns.

2. Placement. Careful observation as to the position of all leads and cables should be made. The original position of all parts and interconnecting leads is shown pictorially in the manual for the equipment.

3. Cleanliness. Careful examination of all corners and recesses in the equipment for the

accumulation of dust should be made. All parts, electrical connectors, and soldered joints should be free of foreign matter.

4. Tightness. All connections, mechanical or electrical, should be checked carefully for tightness.

CLEAN, ADJUST AND TIGHTEN.—These operations are considered to be self-explanatory. Familiarity with the equipment and the service manual will facilitate these operations.

VACUUM TUBES.—The electrician should inspect all glass and metal tube envelopes for accumulation of dust and signs of corrosion. When such signs exist, a potential danger point also exists.

Inspection of the tubes' physical seating within their sockets should be made. This inspection is made by pressing the tubes into their respective sockets. Do not perform this check by withdrawing or rotating the tube forcibly within its socket. Such movements tend to weaken both mechanical and electrical connections associated with the tubes.

All connections to tube sockets should be clean and tight. If the connections show signs of dirt or corrosion, clean them; also tighten them when necessary. Whenever stranded wire is used for electrical connections, observe carefully, using a small mirror when necessary, the placement of each strand of wire. It is possible for single strands to become misplaced, causing external shorts across tube elements.

Periodic cleaning of all vacuum tubes is essential. Do not permit dust or dirt to accumulate on either the tubes or their respective sockets. Remove all dust and dirt from the glass or metal envelopes with a clean, lint-free cloth. When absolutely necessary, it is permissible to remove corrosion, oxidation, or foreign matter from the tube sockets using very fine sandpaper. Never use emery paper.

Examine all tube clamps, caps, and supporting parts to assure a tight fit. These parts are made of heavy gage metal which can withstand the application of pressure.

CAPACITORS.—Inspection of the terminals of all capacitors for corrosion, loose connections, cracks, or signs of breakage should be made. Capacitor mountings should be carefully inspected to discover loose mounting screws, studs, or brackets. Leads must be examined for signs of poor insulation or cracks, and for signs of decay. Frayed strands on the insulation should be cut away.

Variable capacitors should be inspected for any signs of foreign matter lodged between the plates. The operation of the capacitor may be checked by rotating the movable plates.

It is recommended that the plates of variable capacitors be cleaned with a small brush. In no case should the technician use an object that may vary the spacing between the plates.

RESISTORS.—All resistors should be checked for signs of blistering, breaking, chipping, and discoloration. Carefully inspect resistor leads for signs of corrosion, dust, or foreign matter. Resistor leads may become broken at the point of contact with the resistor body. Careful examination will reveal this trouble.

Resistors may be cleaned with a soft brush or a clean, dry cloth. When foreign matter is unusually hard to remove, a suitable authorized solvent may be used. Do not attempt to remove foreign matter from a resistor body by scraping.

FUSES.—Inspect all fuses and fuse holders for evidence of heat and arcing. Usually, burning or overheating will take place when the fuse does not make tight contact with its holder. While fuses are removed, check for signs of corrosion, dirt and foreign matter. When replacing the fuse in the holder, check for loss of tension on replacing the fuse holder cap. Check all wire connections to the fuse holder for tight mechanical and electrical joints.

SWITCHES.—Inspect carefully the mechanical and electrical action of each switch. This is best accomplished by placing the switch in different positions while using your sense of touch, sight, and hearing. Note the freedom of movement and the amount of switch tension in each case. Carefully examine multiple section switches to determine if the contacts are touching and clean. Never attempt to pry wafer contacts apart. All rotary members should make good contact with stationary members on each switch.

Carefully clean all rotary switches with a small brush. Authorized cleaning solvents may be used on contact points when necessary.

POTENTIOMETERS.—Inspect all potentiometers for cleanliness and mechanical action. Potentiometers are protected with dust covers. Do not remove these covers. When evidence indicates that foreign matter exists within the potentiometer structure, send the equipment to a proper maintenance activity for replacement of the potentiometer. Examine the potentiometer structure for loose connections and mounting nuts. Use a soft brush or a dry

cloth to remove dust and dirt from around the potentiometer.

TERMINAL BOARDS.—Inspect all terminal boards for signs of cracks, dirt, breakage, and loose connections. Check the mounting hardware for the terminal boards. Tighten the mounting hardware securely; when tightening, do not exert too much pressure.

Clean terminal boards with a soft brush. Do not disturb electrical connections unless visual checks show cause.

Check conditions of each wire lead attached to the terminals in the terminal boards. Tighten mechanical connectors and good electrical contact should result.

CONNECTORS AND ADAPTERS.—Inspect the exterior and interior of each connector and adapter. Look for any signs of breakage or cracking. Clean each connector and adapter with a dry, clean cloth.

CABLES AND CORDS.—Inspect carefully all cords and cables for cracked or deteriorated insulation. Frayed or cut insulation around connecting and supporting points is a common type of failure. Examine all insulation for signs of oil and grease.

Clean all dust, dirt, and foreign matter from all cables and cords. Dust and dirt commonly hide defects in cable and cord insulation.

PILOT LAMPS.—Inspect pilot lamp assemblies for loose lamps, loose or dirty connectors, and loose mounting nuts. Inspect the pilot lamp for looseness of the glass envelope. Tighten loose lamps in sockets and clean electrical connections to the pilot lamp socket.

TERMINALS.—Inspect terminals periodically for cleanliness and tightness. When replacing faulty terminal lugs, use only an exact replacement. Clean terminals with a stiff brush; when corrosion is present, use crocus cloth.

CABINET AND CHASSIS.—Inspect the interior of the cabinet for cleanliness. Check the control panel for loose knobs and tighten all loose setscrews on control knobs. Wipe all dust, dirt and foreign matter from the exterior and interior of the cabinet with a clean, dry cloth.

GEARS.—Inspect gear teeth on switch drive mechanisms for cleanliness and ease of operation. Clean drive mechanisms with a small brush. If dirt accumulation is great, use an authorized cleaning solvent.

Corrective Maintenance

Corrective maintenance is performed when an actual trouble exists on the equipment. After the repair has been accomplished, calibration of the equipment is necessary.

The electrician is limited to some extent in the corrective maintenance that he is able to perform on test equipments (and still have them function accurately and reliably), principally because he does not have the tools and equipment, and sometimes the spare parts, necessary for this specialized form of maintenance. Therefore the electrician should realize the limitations imposed upon the repair of certain test equipments, and in no case should he attempt repairs until the applicable Service Instruction Manual has been thoroughly read. Particular note should be made of possible circuit misalinement or need for recalibration resulting from parts replacement. In the corrective maintenance section of the test equipment instructions manuals, troubleshooting charts are provided for the localization of trouble. When charts are supplied they should be utilized for the correction of any trouble.

REPAIR.—In repairing a piece of equipment a few preliminary tests, along with a logical procedure, often serve to locate the source of trouble without the use of extensive test equipment. In many cases, the reported symptoms along with a few astute observations will indicate the type and probable location of the trouble. Make observations carefully, and keep the symptoms constantly in mind.

The use of the senses of smell, sight, hearing, and touch often localize the source of trouble rapidly. Note unusual odors, such as sealing compound, which would indicate an overloaded transformer; scorched paint, which could indicate an overheated resistor; and burning rubber, which might point to defective insulation. If any component emits any unusual odor, the trouble might be in that part or in the associated circuit. Examine for smoking parts or sparking. Notice whether wax impregnated capacitors have lost any wax—this is usually indicative of a defective capacitor. Depending, of course, upon the type of test equipment that is faulty, hum, scratch noises, and other odd sounds should have special meaning for the technician.

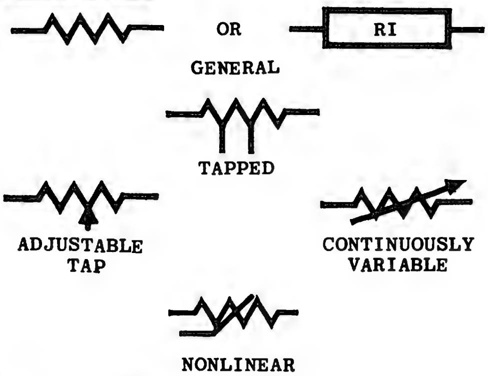
CALIBRATION.—Complete recalibration of test equipment should not be attempted by the technician. For the most accurate calibration of test equipment, precision meters, frequency standards, etc., must be used. These precision equipments are not usually found in a shop where maintenance of aircraft equipment is performed. Accurate calibration of the equipment requires the more complete testing and calibrating instruments which are available at a test equipment repair facility.

Calibration schedules which have been circulated to all fleet activities should be adhered to in order that all test equipment will be accurate.

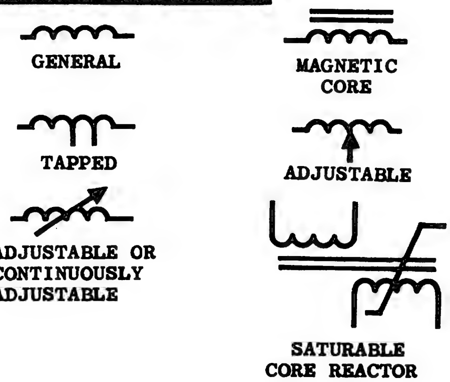
APPENDIX I

ELECTRONIC SYMBOLS

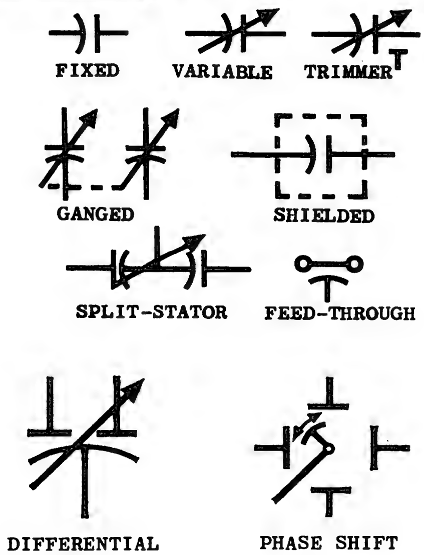
RESISTORS:



INDUCTIVE COMPONENTS:

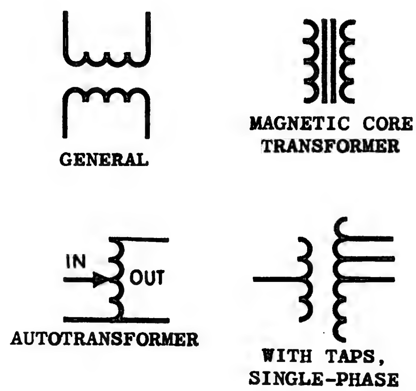


CAPACITORS:



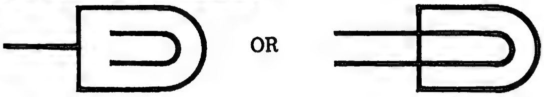
(WHEN CAPACITOR ELECTRODE IDENTIFICATION IS NECESSARY, THE CURVED ELEMENT SHALL REPRESENT THE OUTSIDE ELECTRODE IN FIXED PAPER-DIELECTRIC AND CERAMIC-DIELECTRIC, THE NEGATIVE ELECTRODE IN ELECTROLYTIC CAPACITORS, THE MOVING ELEMENT IN VARIABLE AND ADJUSTABLE CAPACITORS, AND THE LOW POTENTIAL ELEMENT IN FEED-THROUGH CAPACITORS.)

TRANSFORMERS

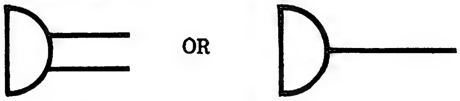


PERMANENT MAGNET

INDICATOR LAMP



MICROPHONE



CRYSTAL

QUARTZ CRYSTAL; PIEZOELECTRIC CRYSTAL UNIT.

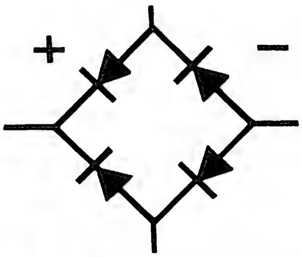
KEY

RECTIFIER

GENERAL

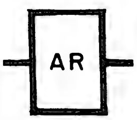
SEMICONDUCTOR

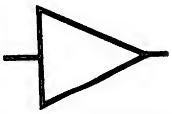
NORMAL CURRENT FLOW IS AGAINST THE ARROW



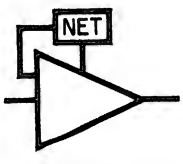
FULL WAVE BRIDGE TYPE

AMPLIFIER





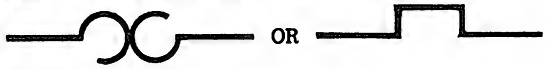
TRIANGLE POINTS IN DIRECTION OF TRANSMISSION (SIGNAL FLOW)



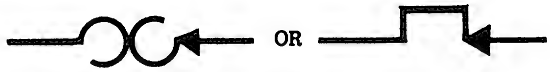
AMPLIFIER WITH EXTERNAL FEEDBACK PATH

BASIC SYMBOL INDICATES ANY METHOD OF AMPLIFICATION EXCEPT THAT OPERATING ON THE PRINCIPLE OF ROTATING MACHINERY.

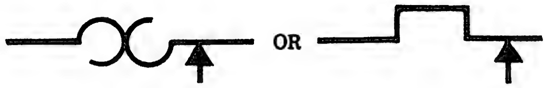
THERMAL ELEMENTS

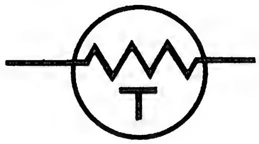


THERMAL RELAY WITH NORMALLY CLOSED CONTACT.

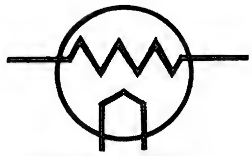


FLASHER; THERMAL CUTOUT

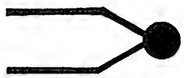




THERMISTOR

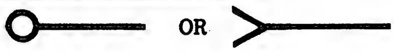


WITH INTEGRAL HEATING ELEMENT

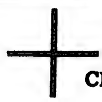


TEMPERATURE-MEASURING THERMOCOUPLE (DISSIMILAR METAL DEVICE)

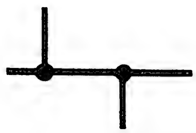
INPUTS (NONSTANDARD)



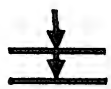
PATH, TRANSMISSION



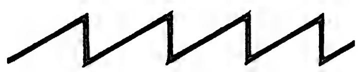
CROSSING NOT CONNECTED



JUNCTION CONNECTED



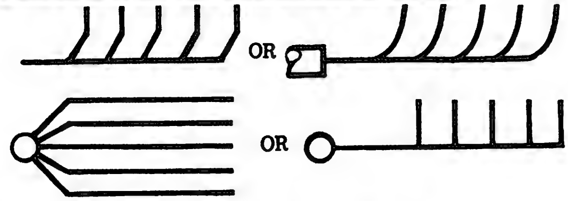
TWISTED PAIR



AIR OR SPACE PATH

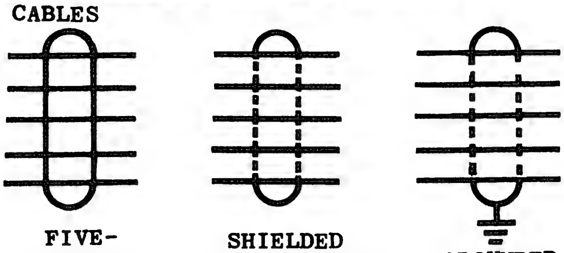
COAXIAL

GROUPING OF WIRES IN BUNDLES



GROUPING OF WIRES IN CABLES

CABLES



FIVE-CONDUCTOR CABLE

SHIELDED FIVE-CONDUCTOR CABLE

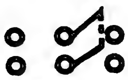
GROUNDED SHIELD

NUMBER OF CONDUCTORS MAY BE ONE OR MORE AS NECESSARY

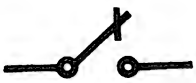
SWITCHES

GENERAL (SINGLE THROW)

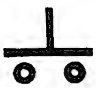
GENERAL (DOUBLE THROW)



TWO POLE DOUBLE THROW SWITCH

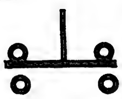


KNIFE SWITCH



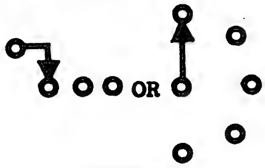
PUSHBUTTON (MAKE)

PUSHBUTTON (BREAK)



PUSHBUTTON TWO CIRCUIT

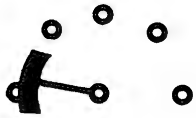
SELECTOR SWITCHES

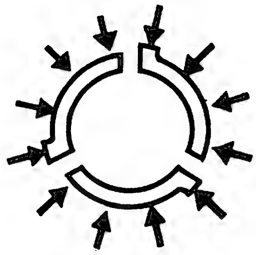


GENERAL

ANY NUMBER OF TRANSMISSION PATHS MAY BE SHOWN. ALSO BREAK BEFORE MAKE SWITCH.

MAKE BEFORE BREAK





WAFER, TYPICAL 3-POLE, 3-CIRCUIT SWITCH. VIEWED FROM END OPPOSITE CONTROL KNOB. FOR MORE THAN ONE SECTION, #1 IS NEAREST CONTROL KNOB.

CIRCUIT RETURNS

CHASSIS CONNECTION

(THE CHASSIS OR FRAME IS NOT NECESSARILY AT GROUND POTENTIAL.)

GROUND

CONTACTS (ELECTRICAL)

SWITCH

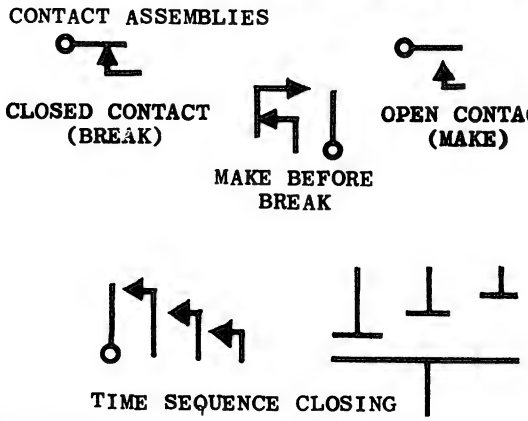
MOMENTARY SWITCH

LOCKING

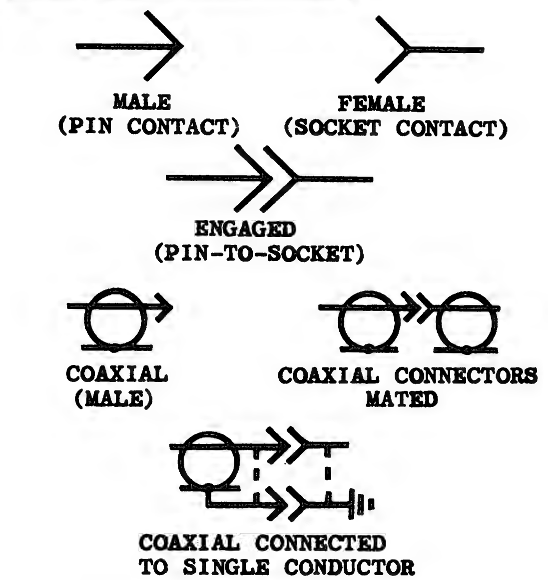
NONLOCKING

FOR JACK, KEY, RELAY, ETC.

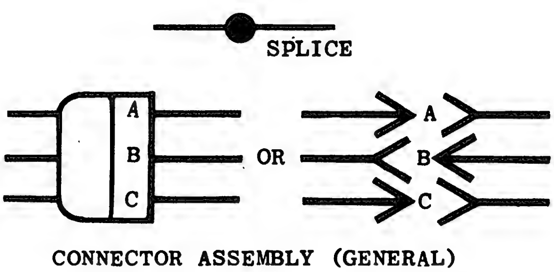
CONTACTS (ELECTRICAL) (Continued)



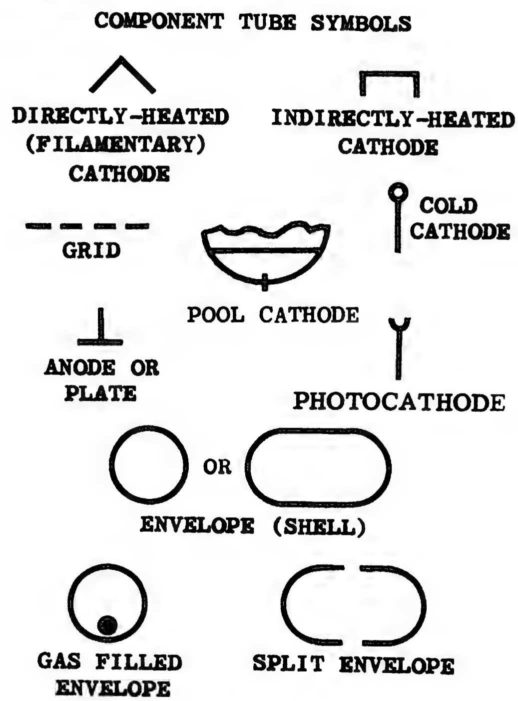
DISCONNECTING DEVICES



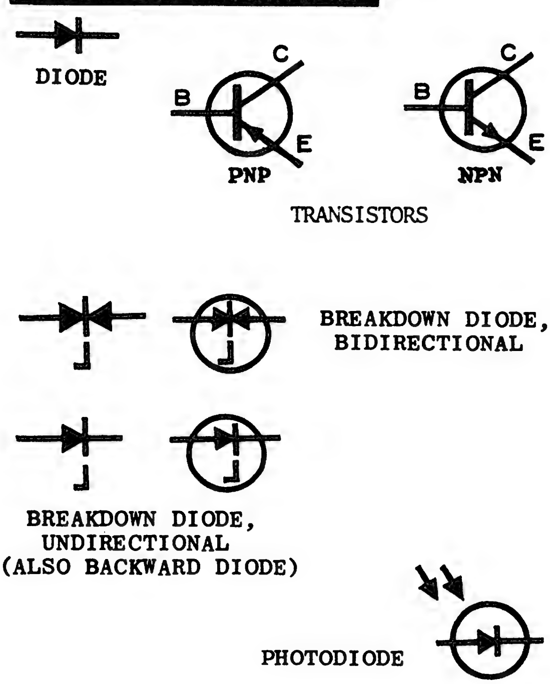
THE CONNECTOR SYMBOL IS NOT AN ARROWHEAD. IT IS LARGER AND THE LINES ARE DRAWN AT A 90° ANGLE.



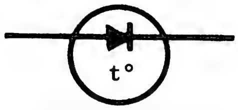
ELECTRON TUBES



SEMICONDUCTOR DEVICES

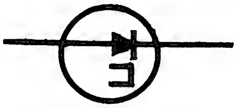


SEMICONDUCTOR DEVICES: (Continued)



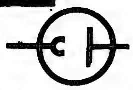
TEMPERATURE DEPENDENT DIODE


PNPN SWITCH

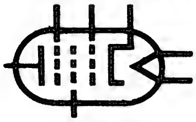

TUNNEL DIODE

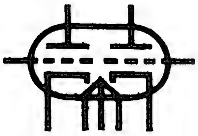
TYPICAL ELECTRON TUBES

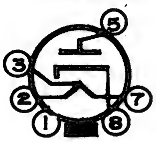

COLD CATHODE GAS TUBE

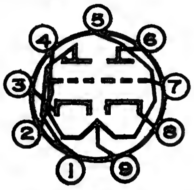

PHOTOTUBE SINGLE UNIT, VACUUM


DIODE

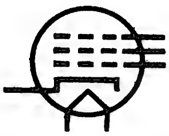

PENTODE


TWIN TRIODE ILLUSTRATING ELONGATED ENVELOPE


DIODE SHOWING BASE CONNECTIONS

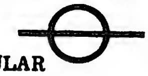

TWIN TRIODE WITH TAPPED HEATER

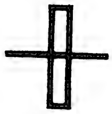
TYPICAL CATHODE RAY TUBES


MAGNETIC DEFLECTION

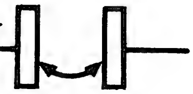

ELECTROSTATIC DEFLECTION

WAVEGUIDES

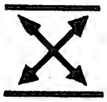

CIRCULAR

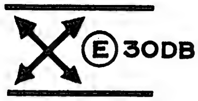

RECTANGULAR


RIDGED


ROTARY JOINT

DIRECTIONAL COUPLERS


GENERAL



E PLANE APERTURE COUPLING, 30 DB TRANSMISSION LOSS

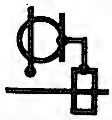
COUPLING METHODS

GENERALLY USED FOR COAXIAL AND WAVEGUIDE TRANSMISSION.

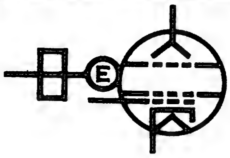

COUPLING BY APERTURE WITH AN OPENING OF LESS THAN FULL WAVEGUIDE SIZE. TYPE OF COUPLING WILL BE INDICATED WITHIN CIRCLE (E, H, OR HE).


COUPLING BY LOOP TO SPACE

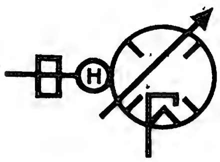

COUPLING BY LOOP TO GUIDED TRANSMISSION PATH


COUPLING BY PROBE FROM COAXIAL TO RECTANGULAR WAVEGUIDE WITH DIRECT-CURRENT GROUNDS CONNECTED

TYPICAL MAGNETRONS AND KLYSTRONS

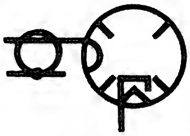


REFLEX KLYSTRON, APERATURE COUPLED

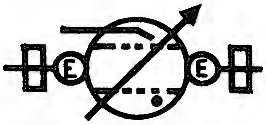


TUNABLE MAGNETRON, APERTURE COUPLED

TYPICAL MAGNETRONS AND KLYSTRONS (Continued)



RESONANT TYPE WITH COAXIAL OUTPUT



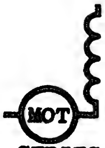
TRANSMIT-RECEIVE (TR) TUBE GAS FILLED, TUNABLE INTEGRAL CAVITY, APERTURE COUPLED, WITH STARTER

ROTATING MACHINES

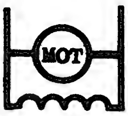
MOTOR

GENERATOR

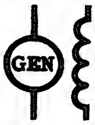
TYPES OF WINDINGS



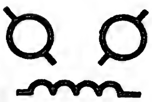
SERIES



SHUNT



SEPARATELY EXCITED



DYNAMOTOR

WINDING SYMBOLS

SINGLE-PHASE

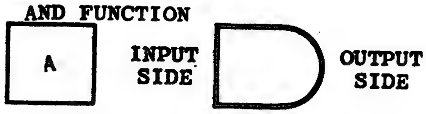
TWO - PHASE

THREE-PHASE (WYE)

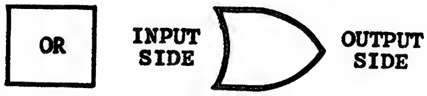
THREE-PHASE (DELTA)

LOGIC FUNCTIONS

AND FUNCTION



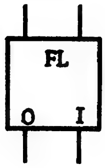
INCLUSIVE OR FUNCTION



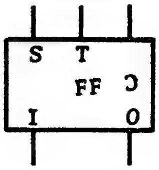
EXCLUSIVE OR FUNCTION

FLIP-FLOPS

LATCH



COMPLEMENTARY

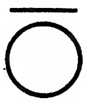


S-SET T-TRIGGER C-CLEAR

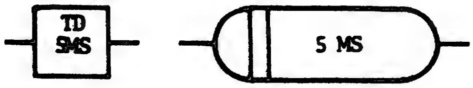
NEGATION

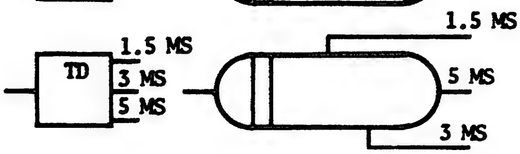
0

ELECTRIC INVERTER



TIME DELAY





LOGIC FUNCTIONS (Continued)

SINGLE SHOT

SCHMITT TRIGGER

OSCILLATOR

SYNCHROS

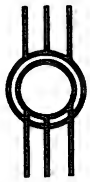
GENERAL

A LETTER COMBINATION FROM THE FOLLOWING LIST MAY BE PLACED ADJACENT TO THE SYMBOL TO INDICATE THE TYPE OF SYNCHRO:

- TX - TORQUE TRANSMITTER
- TDX - TORQUE DIFFERENTIAL TRANSMITTER
- CX - CONTROL TRANSMITTER
- CDX - CONTROL DIFFERENTIAL TRANSMITTER
- TR - TORQUE RECEIVER
- CT - CONTROL TRANSFORMER

SYNCHROS (Continued)

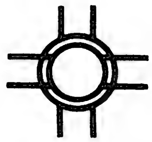
TRANSMITTER, RECEIVER, OR CONTROL TRANSFORMER



DIFFERENTIAL TRANSMITTER OR RECEIVER

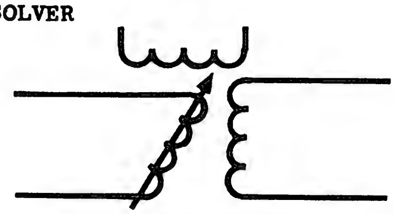
RESOLVER (SYNCHRO)

SINGLY-WOUND ROTOR

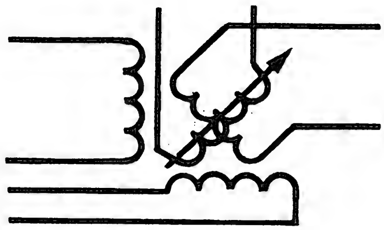


DOUBLY-WOUND ROTOR

RESOLVER

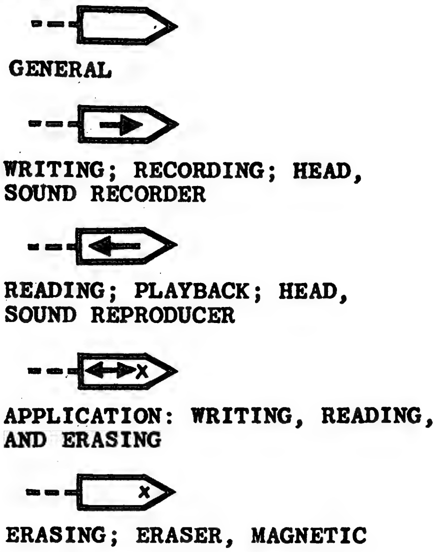


SINGLY-WOUND ROTOR

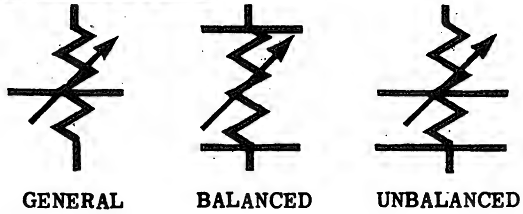


DOUBLY-WOUND ROTOR

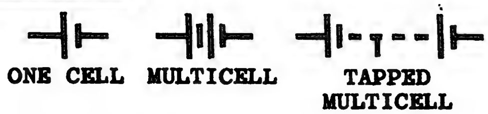
PICKUP HEADS



ATTENUATORS

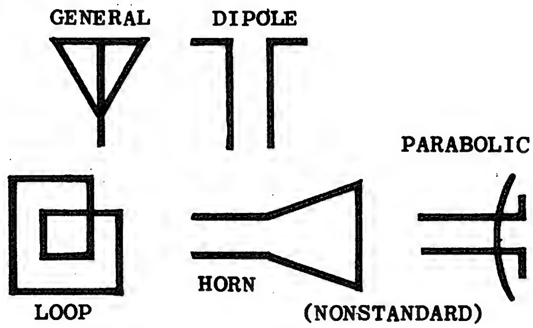


BATTERIES



(LONG LINE IS ALWAYS POSITIVE)

ANTENNAS

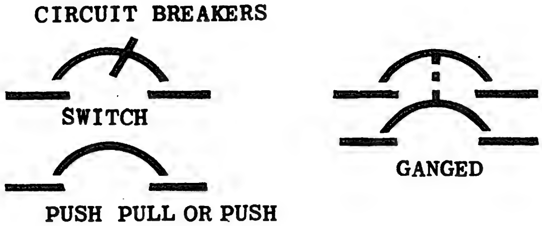


(NONSTANDARD)

CIRCUIT PROTECTORS

FUSE

CIRCUIT BREAKERS



METERS

A - AMMETER

CRO - OSCILLOSCOPE

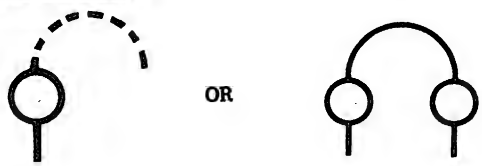
G - GALVANOMETER

MA - MILLIAMMETER

OHM - OHMMETER

V - VOLTMETER

HEADSET



APPENDIX II

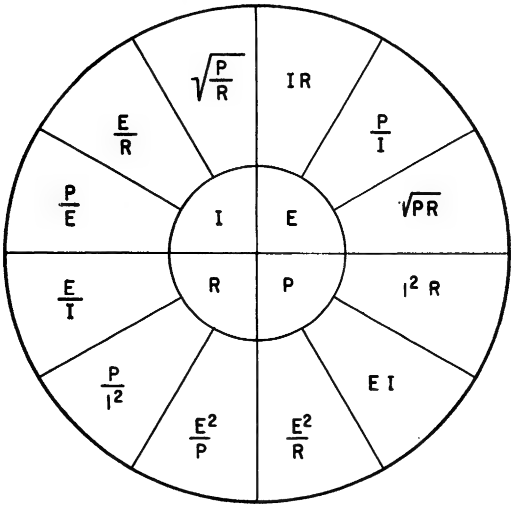
GREEK ALPHABET

Name	Capital	Lower Case	Designates
Alpha	A	α	Angles, coefficient of thermal expansion.
Beta.	B	β	Angles, flux density.
Gamma.	Γ	γ	Conductivity.
Delta	Δ	δ	Variation of a quantity, increment.
Epsilon.	E	ϵ	Base of natural logarithms (2. 71828).
Zeta.	Z	ζ	Impedance, coefficients, coordinates.
Eta	H	η	Hysteresis coefficient, efficiency, magnetizing force.
Theta	Θ	θ	Phase angle.
Iota	I	ι	
Kappa	K	κ	Dielectric constant, coupling coefficient, susceptibility.
Lambda	Λ	λ	Wavelength.
Mu.	M	μ	Permeability, micro, amplification factor.
Nu	N	ν	Reluctivity.
Xi	Ξ	ξ	
Omicron	O	o	
Pi	Π	π	3. 1416
Rho	P	ρ	Resistivity.
Sigma.	Σ	σ	Summation symbol (cap).
Tau	T	τ	Time constant, time-phase displacement.
Upsilon.	Υ	υ	
Phi	Φ	φ	Angles, magnetic flux.
Chi	X	χ	
Psi	Ψ	ψ	Dielectric flux, phase difference.
Omega	Ω	ω	Ohms (capital), angular velocity ($2 \pi f$).

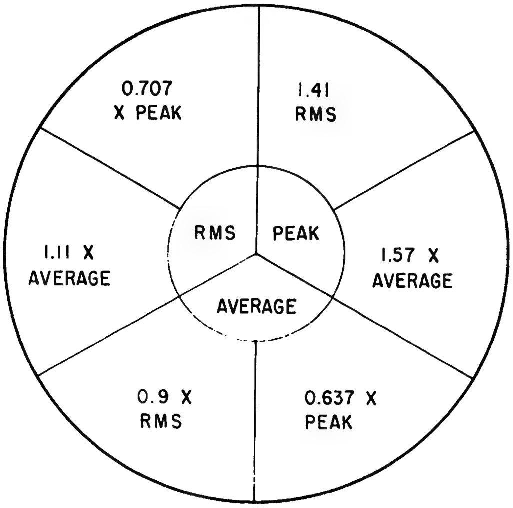
APPENDIX III

ELECTRICAL/MATHEMATICAL RELATIONSHIP

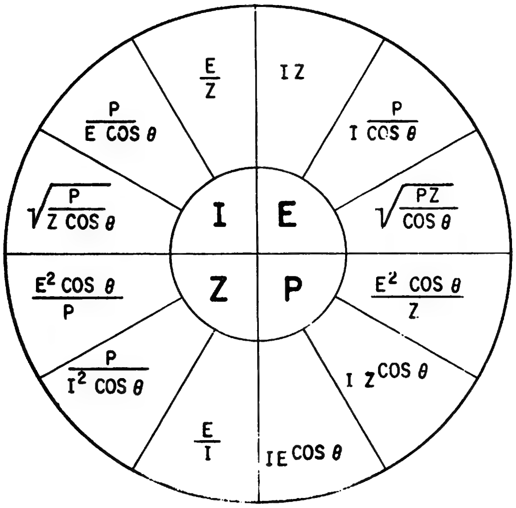
OHMS LAW FOR D-C CIRCUITS



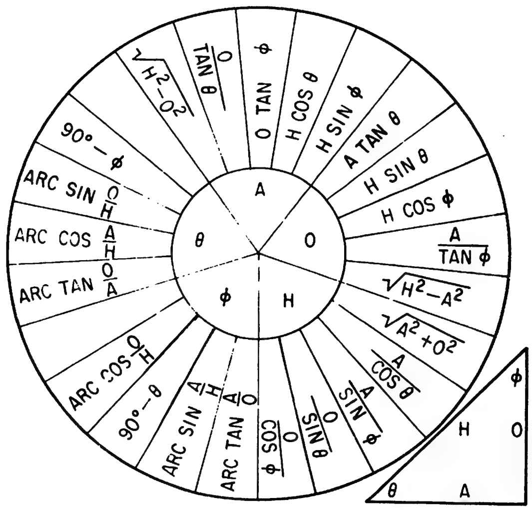
A-C VOLTAGE RELATIONS



OHMS LAW FOR A-C CIRCUITS



FUNCTIONS OF A RIGHT ANGLE



POWER FACTOR $\frac{EI \cos\theta}{EI}$

RATIO $\frac{\text{NAUTICAL MILE}}{\text{STATUTE MILE}} = \frac{7.60}{6.60}$

CIRCULAR MILS $= \frac{\text{SQ. MILS}}{0.7854}$

ONE RADIAN $= \frac{360°}{2\pi} = 57.3°$

RADIANS = DEGREES x 0.0175

SECONDS OF ARC $= 206265 = \frac{360° \times 60' \times 60''}{2\pi}$

MINUTES OF ARC $= 3438 = \frac{360° \times 60'}{2\pi}$

APPENDIX IV

TRIGONOMETRIC FUNCTIONS

In a right triangle, there are several relationships which always hold true. These relationships pertain to the lengths of the sides of a right triangle, and the way the lengths are affected by the angles between them. An understanding of these relationships, called trigonometric functions, is essential for solving many problems in a-c circuits such as power factor, impedance, voltage drops, and so forth.

To be a RIGHT triangle, a triangle must have a "square" corner; one in which there is exactly 90° between two of the sides. Trigonometric functions do not apply to any other type of triangle. This type of triangle is shown in figure V-1.

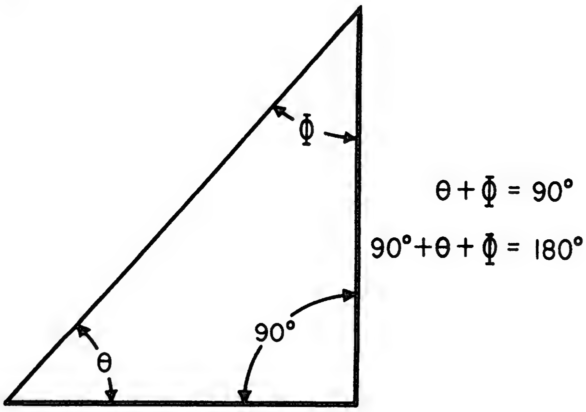


Figure V-1. —A right triangle.

By use of the trigonometric functions, it is possible to determine the UNKNOWN length of one or more sides of a triangle, or the number of degrees in UNKNOWN angles, depending on what is presently known about the triangle. For instance, if the lengths of any two sides are known, the third side and both angles Θ (theta) and Φ (phi) may be determined. The triangle may also be solved if the length of any one side and one of the angles (Θ or Φ in fig. V-1) are known.

The first basic fact to accept, regarding triangles, is that in any triangle, the sum of the three angles formed inside the triangle must always equal 180°. If one angle is always 90° (a right angle) then the sum of the other two angles must always be 90°.

$$\Theta + \Phi = 90°$$

and

$$90° + \Theta + \Phi = 180°$$

or

$$90° + 90° = 180°$$

Thus, if angle Θ is known, Φ may be quickly determined.

For instance, if Θ is 30°, what is Φ?

$$90° + 30° + \Phi = 180°$$

Transposing

$$\Phi = 180° - 90° - 30°$$

$$\Phi = 60°$$

Also, if Φ is known, Θ may be determined in the same manner.

The second basic fact you must understand is that for every different combination of angles in a triangle, there is a definite ratio between the lengths of the three sides. Consider the triangle in figure V-2, consisting of the base, side B; the altitude, side A; and the hypotenuse, side C. (The hypotenuse is always the longest side, and is always opposite the 90° angle.) If angle Θ is 30°, Φ must be 60°. With Θ equal to 30°, the ratio of the length of side B to side C is 0.866 to 1. That is, if the hypotenuse is 1 inch long, the side adjacent to Θ, side B, is 0.866 inch long. Also, with Θ equal to 30°, the ratio of side A to side C is 0.5 to 1. That is, with the hypotenuse 1 inch long, the side opposite to Θ (side A) is 0.5 inch long. With Θ still at 30°, side A is 0.5774 of the length of B. With the combination of angles given (30° - 60° - 90°) these are the ONLY ratios of lengths that will "fit" to form a right triangle.

Note that three ratios are shown to exist for the given value of Θ: the ratio $\frac{B}{C}$, which is always referred to as the COSINE ratio of Θ, the ratio $\frac{A}{C}$, which is always the SINE ratio of Θ, and the ratio $\frac{A}{B}$, which is always the TANGENT ratio of Θ. If Θ changes, all three ratios change, because the lengths of the sides (base and altitude) change. There is a set of ratios for every increment between 0° and 90°.

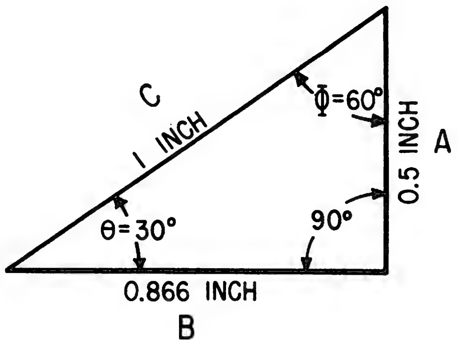


Figure V-2. —A 30°-60°-90° triangle.

These angular ratios, or sine, cosine, and tangent functions, are listed for each degree and tenth of degree in a table at the end of this appendix. In this table, the length of the hypotenuse of a triangle is considered fixed. Thus, the ratios of length given refer to the manner in which sides A and B vary with relation to each other and in relation to side C, as angle Θ is varied from 0° to 90°.

The solution of problems in trigonometry (solution of triangles) is made much simpler when the table of trigonometric functions is used properly. The most common ways in which it is used will be shown by solving a series of exemplary problems.

PROBLEM 1: If the hypotenuse of the triangle (side C) in figure V-3 (A) is 10 inches long, and angle Θ is 33°, how long are sides B and A? SOLUTION: The ratio $\frac{B}{C}$ is the cosine function. By checking the table of functions, you will find that the cosine of 33° is 0.8387. This means that the length of B is 0.8387 the length of side C. If side C is 10 inches long, then side B must be 10 x 0.8387, or 8.387 inches in length. To determine the length of side A, use the sine function, the ratio $\frac{A}{C}$. Again consulting the table of functions, you will find that the sine of 33° is 0.5446. Thus, side A must be 10 x 0.5446, or 5.446 inches in length.

PROBLEM 2: The triangle in figure V-3 (B) has a base 74.2 feet long, and a hypotenuse 100 feet long. What is Θ , and how long is side A? SOLUTION: When no angles are given, you must always solve for a known angle first. The ratio $\frac{B}{C}$ is the cosine of the unknown angle Θ; therefore $\frac{74.2}{100}$, or 0.742, is the cosine of the unknown angle. Locating 0.742 as a cosine value in the table, you find that it is the cosine of 42.1°. That is, Θ = 42.1°. With Θ known, side A is solved for by use of the sine ratio $\frac{A}{C}$. The sine

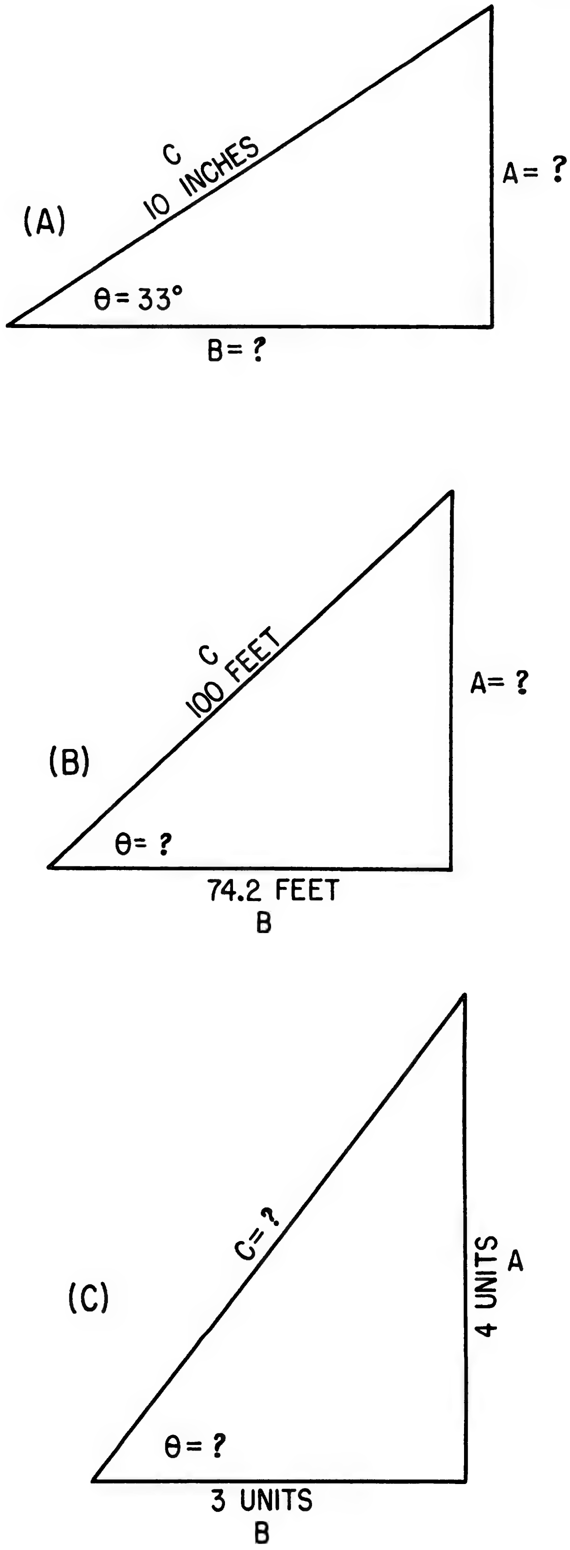


Figure V-3. —Trigonometric problems.

of 42.1°, according to the table, is 0.6704. Therefore, side A is 100 x 0.6704, or 67.04 feet long.

PROBLEM 3: In the triangle in figure VI-3 (C), the base is 3 units long, and the altitude is 4 units. What is Θ, and how long is the hypotenuse? SOLUTION: With the information given, the tangent of Θ may be determined. Tan $\Theta = \frac{A}{B} = \frac{4}{3} = 1.33$. Locating the value 1.33 as a tangent value in the table of functions, you find it to be the tangent of 53.2°. Therefore, Θ = 53.2°. Once Θ is known, either the sine or cosine ratio may be used to determine the length of the hypotenuse. The cosine of 53.2° is 0.6004. This indicates that the base of 3 units is 0.6004 x the length of the hypotenuse. Therefore, the hypotenuse is $\frac{3}{0.6004}$, or 5 units in length. Using the sine ratio, the hypotenuse is $\frac{3}{0.7997}$, or 5 units in length.

In the foregoing explanations and problems, the sides of triangles were given in inches, feet and units. In applying trigonometry to a-c circuit problems, these units of measure will be replaced by such measurements as ohms, amperes, volts, and watts. Angle Θ will often be referred to as the phase angle. However, the solution of these a-c problems is accomplished in exactly the same manner as the foregoing problems. Only the units and some terminology are changed.

APPENDIX V

NATURAL SINES, COSINES, AND TANGENTS

0°–14.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
0	sin	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157
	cos	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
	tan	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157
1	sin	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332
	cos	0.9998	0.9998	0.9998	0.9997	0.9997	0.9997	0.9996	0.9996	0.9995	0.9995
	tan	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332
2	sin	0.0349	0.0366	0.0384	0.0401	0.0419	0.0436	0.0454	0.0471	0.0488	0.0506
	cos	0.9994	0.9993	0.9993	0.9992	0.9991	0.9990	0.9990	0.9989	0.9988	0.9987
	tan	0.0349	0.0367	0.0384	0.0402	0.0419	0.0437	0.0454	0.0472	0.0489	0.0507
3	sin	0.0523	0.0541	0.0558	0.0576	0.0593	0.0610	0.0628	0.0645	0.0663	0.0680
	cos	0.9986	0.9985	0.9984	0.9983	0.9982	0.9981	0.9980	0.9979	0.9978	0.9977
	tan	0.0524	0.0542	0.0559	0.0577	0.0594	0.0612	0.0629	0.0647	0.0664	0.0682
4	sin	0.0698	0.0715	0.0732	0.0750	0.0767	0.0785	0.0802	0.0819	0.0837	0.0854
	cos	0.9976	0.9974	0.9973	0.9972	0.9971	0.9969	0.9968	0.9966	0.9965	0.9963
	tan	0.0699	0.0717	0.0734	0.0752	0.0769	0.0787	0.0805	0.0822	0.0840	0.0857
5	sin	0.0872	0.0889	0.0906	0.0924	0.0941	0.0958	0.0976	0.0993	0.1011	0.1028
	cos	0.9962	0.9960	0.9959	0.9957	0.9956	0.9954	0.9952	0.9951	0.9949	0.9947
	tan	0.0875	0.0892	0.0910	0.0928	0.0945	0.0963	0.0981	0.0998	0.1016	0.1033
6	sin	0.1045	0.1063	0.1080	0.1097	0.1115	0.1132	0.1149	0.1167	0.1184	0.1201
	cos	0.9945	0.9943	0.9942	0.9940	0.9938	0.9936	0.9934	0.9932	0.9930	0.9928
	tan	0.1051	0.1069	0.1086	0.1104	0.1122	0.1139	0.1157	0.1175	0.1192	0.1210
7	sin	0.1219	0.1236	0.1253	0.1271	0.1288	0.1305	0.1323	0.1340	0.1357	0.1374
	cos	0.9925	0.9923	0.9921	0.9919	0.9917	0.9914	0.9912	0.9910	0.9907	0.9905
	tan	0.1228	0.1246	0.1263	0.1281	0.1299	0.1317	0.1334	0.1352	0.1370	0.1388
8	sin	0.1392	0.1409	0.1426	0.1444	0.1461	0.1478	0.1495	0.1513	0.1530	0.1547
	cos	0.9903	0.9900	0.9898	0.9895	0.9893	0.9890	0.9888	0.9885	0.9882	0.9880
	tan	0.1405	0.1423	0.1441	0.1459	0.1477	0.1495	0.1512	0.1530	0.1548	0.1566
9	sin	0.1564	0.1582	0.1599	0.1616	0.1633	0.1650	0.1668	0.1685	0.1702	0.1719
	cos	0.9877	0.9874	0.9871	0.9869	0.9866	0.9863	0.9860	0.9857	0.9854	0.9851
	tan	0.1584	0.1602	0.1620	0.1638	0.1655	0.1673	0.1691	0.1709	0.1727	0.1745
10	sin	0.1736	0.1754	0.1771	0.1788	0.1805	0.1822	0.1840	0.1857	0.1874	0.1891
	cos	0.9848	0.9845	0.9842	0.9839	0.9836	0.9833	0.9829	0.9826	0.9823	0.9620
	tan	0.1763	0.1781	0.1799	0.1817	0.1835	0.1853	0.1871	0.1890	0.1908	0.1926
11	sin	0.1908	0.1925	0.1942	0.1959	0.1977	0.1994	0.2011	0.2028	0.2045	0.2062
	cos	0.9816	0.9813	0.9810	0.9806	0.9803	0.9799	0.9796	0.9792	0.9789	0.9785
	tan	0.1944	0.1962	0.1980	0.1998	0.2016	0.2035	0.2053	0.2071	0.2089	0.2107
12	sin	0.2079	0.2096	0.2113	0.2130	0.2147	0.2164	0.2181	0.2198	0.2215	0.2232
	cos	0.9781	0.9778	0.9774	0.9770	0.9767	0.9763	0.9759	0.9755	0.9751	0.9748
	tan	0.2126	0.2144	0.2162	0.2180	0.2199	0.2217	0.2235	0.2254	0.2272	0.2290
13	sin	0.2250	0.2267	0.2284	0.2300	0.2318	0.2334	0.2351	0.2368	0.2385	0.2402
	cos	0.9744	0.9740	0.9736	0.9732	0.9728	0.9724	0.9720	0.9715	0.9711	0.9707
	tan	0.2309	0.2327	0.2345	0.2364	0.2382	0.2401	0.2419	0.2438	0.2456	0.2476
14	sin	0.2419	0.2436	0.2453	0.2470	0.2487	0.2504	0.2521	0.2538	0.2554	0.2571
	cos	0.9703	0.9699	0.9694	0.9690	0.9686	0.9681	0.9677	0.9673	0.9668	0.9664
	tan	0.2493	0.2512	0.2530	0.2549	0.2568	0.2586	0.2605	0.2623	0.2642	0.2661
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

15°–29.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
15	sin	0.2588	0.2605	0.2622	0.2639	0.2656	0.2672	0.2689	0.2706	0.2723	0.2740
	cos	0.9659	0.9655	0.9650	0.9646	0.9641	0.9636	0.9632	0.9627	0.9622	0.9617
	tan	0.2679	0.2698	0.2717	0.2736	0.2754	0.2773	0.2792	0.2811	0.2830	0.2849
16	sin	0.2756	0.2773	0.2790	0.2807	0.2823	0.2840	0.2857	0.2874	0.2890	0.2907
	cos	0.9613	0.9608	0.9603	0.9598	0.9593	0.9588	0.9583	0.9578	0.9573	0.9568
	tan	0.2867	0.2886	0.2905	0.2924	0.2943	0.2962	0.2981	0.3000	0.3019	0.3038
17	sin	0.2924	0.2940	0.2957	0.2974	0.2990	0.3007	0.3024	0.3040	0.3057	0.3074
	cos	0.9563	0.9558	0.9553	0.9548	0.9542	0.9537	0.9532	0.9527	0.9521	0.9516
	tan	0.3057	0.3076	0.3096	0.3115	0.3134	0.3153	0.3172	0.3191	0.3211	0.3230
18	sin	0.3090	0.3107	0.3123	0.3140	0.3156	0.3173	0.3190	0.3206	0.3223	0.3239
	cos	0.9511	0.9505	0.9500	0.9494	0.9489	0.9483	0.9478	0.9472	0.9466	0.9461
	tan	0.3249	0.3269	0.3288	0.3307	0.3327	0.3346	0.3365	0.3385	0.3404	0.3424
19	sin	0.3256	0.3272	0.3289	0.3305	0.3322	0.3338	0.3355	0.3371	0.3387	0.3404
	cos	0.9455	0.9449	0.9444	0.9438	0.9432	0.9426	0.9421	0.9415	0.9409	0.9403
	tan	0.3443	0.3463	0.3482	0.3502	0.3522	0.3541	0.3561	0.3581	0.3600	0.3620
20	sin	0.3420	0.3437	0.3453	0.3469	0.3486	0.3502	0.3518	0.3535	0.3551	0.3567
	cos	0.9397	0.9391	0.9385	0.9379	0.9373	0.9367	0.9361	0.9354	0.9348	0.9342
	tan	0.3640	0.3659	0.3679	0.3699	0.3719	0.3739	0.3759	0.3779	0.3799	0.3819
21	sin	0.3584	0.3600	0.3616	0.3633	0.3649	0.3665	0.3681	0.3697	0.3714	0.3730
	cos	0.9336	0.9330	0.9323	0.9317	0.9311	0.9304	0.9298	0.9291	0.9285	0.9278
	tan	0.3839	0.3859	0.3879	0.3899	0.3919	0.3939	0.3959	0.3979	0.4000	0.4020
22	sin	0.3746	0.3762	0.3778	0.3795	0.3811	0.3827	0.3843	0.3859	0.3875	0.3891
	cos	0.9272	0.9265	0.9259	0.9252	0.9245	0.9239	0.9232	0.9225	0.9219	0.9212
	tan	0.4040	0.4061	0.4061	0.4101	0.4122	0.4142	0.4163	0.4183	0.4204	0.4224
23	sin	0.3907	0.3923	0.3939	0.3955	0.3971	0.3987	0.4003	0.4019	0.4035	0.4051
	cos	0.9205	0.9198	0.9191	0.9184	0.9178	0.9171	0.9164	0.9157	0.9150	0.9143
	tan	0.4245	0.4265	0.4286	0.4307	0.4327	0.4348	0.4369	0.4390	0.4411	0.4431
24	sin	0.4067	0.4083	0.4099	0.4115	0.4131	0.4147	0.4163	0.4179	0.4195	0.4210
	cos	0.9135	0.9128	0.9121	0.9114	0.9107	0.9100	0.9092	0.9085	0.9078	0.9070
	tan	0.4452	0.4473	0.4494	0.4515	0.4536	0.4557	0.4578	0.4599	0.4621	0.4642
25	sin	0.4226	0.4242	0.4258	0.4274	0.4289	0.4305	0.4321	0.4337	0.4352	0.4368
	cos	0.9063	0.90[illegible]6	0.9048	0.9041	0.9033	0.9026	0.9018	0.9011	0.9003	0.8996
	tan	0.4663	0.4684	0.4706	0.4727	0.4748	0.4770	0.4791	0.4813	0.4834	0.4856
26	sin	0.4384	0.4399	0.4415	0.4431	0.4446	0.4462	0.4478	0.4493	0.4509	0.4524
	cos	0.8988	0.8980	0.8073	0.8965	0.8957	0.8949	0.8942	0.8934	0.8926	0.8918
	tan	0.4877	0.4899	0.4921	0.4942	0.4964	0.4986	0.5008	0.5029	0.5051	0.5073
27	sin	0.4540	0.4555	0.4571	0.4586	0.4602	0.4617	0.4633	0.4648	0.4664	0.4679
	cos	0.8910	0.8902	0.8894	0.8886	0.8878	0.8870	0.8862	0.8854	0.8846	0.8838
	tan	0.5095	0.5117	0.5139	0.5161	0.5184	0.5206	0.5228	0.5250	0.5272	0.5295
28	sin	0.4695	0.4710	0.4726	0.4741	0.4756	0.4772	0.4787	0.4802	0.4818	0.4833
	cos	0.8829	0.8821	0.8813	0.8805	0.8796	0.8788	0.8780	0.8771	0.8763	0.8755
	tan	0.5317	0.5340	0.5362	0.5384	0.5407	0.5430	0.5452	0.5475	0.5498	0.5520
29	sin	0.4848	0.4863	0.4879	0.4894	0.4909	0.4924	0.4939	0.4955	0.4970	0.4985
	cos	0.8746	0.8738	0.8729	0.8721	0.8712	0.8704	0.8695	0.8686	0.8678	0.8669
	tan	0.5543	0.5566	0.5589	0.5612	0.5635	0.5658	0.5681	0.5704	0.5727	0.5750
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

30°–44.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
30	sin	0.5000	0.5015	0.5030	0.5045	0.5060	0.5075	0.5090	0.5105	0.5120	0.5135
	cos	0.8660	0.8652	0.8643	0.8634	0.8625	0.8616	0.8607	0.8599	0.8590	0.8581
	tan	0.5774	0.5797	0.5820	0.5844	0.5867	0.5890	0.5914	0.5938	0.5961	0.5985
31	sin	0.5150	0.5165	0.5180	0.5195	0.5210	0.5225	0.5240	0.5255	0.5270	0.5284
	cos	0.8572	0.8563	0.8554	0.8545	0.8536	0.8526	0.8517	0.8508	0.8499	0.8490
	tan	0.6009	0.6032	0.6056	0.6080	0.6104	0.6128	0.6152	0.6176	0.6200	0.6224
32	sin	0.5299	0.5314	0.5329	0.5344	0.5358	0.5373	0.5388	0.5402	0.5417	0.5432
	cos	0.8480	0.8471	0.8462	0.8453	0.8443	0.8434	0.8425	0.8415	0.8406	0.8396
	tan	0.6249	0.6273	0.6297	0.6322	0.6346	0.6371	0.6395	0.6420	0.6445	0.6469
33	sin	0.5446	0.5461	0.5476	0.5490	0.5505	0.5519	0.5534	0.5548	0.5563	0.5577
	cos	0.8387	0.8377	0.8368	0.8358	0.8348	0.8339	0.8329	0.8320	0.8310	0.8300
	tan	0.6494	0.6519	0.6544	0.6569	0.6594	0.6619	0.6644	0.6669	0.6694	0.6720
34	sin	0.5592	0.5606	0.5621	0.5635	0.5650	0.5664	0.5678	0.5693	0.5707	0.5721
	cos	0.8290	0.8281	0.8271	0.8261	0.8251	0.8241	0.8231	0.8221	0.8211	0.8202
	tan	0.6745	0.6771	0.6796	0.6822	0.6847	0.6873	0.6899	0.6924	0.6950	0.6976
35	sin	0.5736	0.5750	0.5764	0.5779	0.5793	0.5807	0.5821	0.5835	0.5850	0.5864
	cos	0.8192	0.8181	0.8171	0.8161	0.8151	0.8141	0.8131	0.8121	0.8111	0.8100
	tan	0.7002	0.7028	0.7054	0.7080	0.7107	0.7133	0.7159	0.7186	0.7212	0.7239
36	sin	0.5878	0.5892	0.5906	0.5920	0.5934	0.5948	0.5962	0.5976	0.5990	0.6004
	cos	0.8090	0.8080	0.8070	0.8059	0.8049	0.8039	0.8028	0.8018	0.8007	0.7997
	tan	0.7265	0.7292	0.7319	0.7346	0.7373	0.7400	0.7427	0.7454	0.7481	0.7508
37	sin	0.6018	0.6032	0.6046	0.6060	0.6074	0.6088	0.6101	0.6115	0.6129	0.6143
	cos	0.7986	0.7976	0.7965	0.7955	0.7944	0.7934	0.7923	0.7912	0.7902	0.7891
	tan	0.7536	0.7563	0.7590	0.7618	0.7646	0.7673	0.7701	0.7729	0.7757	0.7785
38	sin	0.6157	0.6170	0.6184	0.6198	0.6211	0.6225	0.6239	0.6252	0.6266	0.6280
	cos	0.7880	0.7869	0.7859	0.7848	0.7837	0.7826	0.7815	0.7804	0.7793	0.7782
	tan	0.7813	0.7841	0.7869	0.7898	0.7926	0.7954	0.7983	0.8012	0.8040	0.8069
39	sin	0.6293	0.6307	0.6320	0.6334	0.6347	0.6361	0.6374	0.6388	0.6401	0.6414
	cos	0.7771	0.7760	0.7749	0.7738	0.7727	0.7716	0.7705	0.7694	0.7683	0.7672
	tan	0.8098	0.8127	0.8156	0.8185	0.8214	0.8243	0.8273	0.8302	0.8332	0.8361
40	sin	0.6428	0.6441	0.6455	0.6468	0.6481	0.6494	0.6508	0.6521	0.6534	0.6547
	cos	0.7660	0.7649	0.7638	0.7627	0.7615	0.7604	0.7593	0.7581	0.7570	0.7559
	tan	0.8391	0.8421	0.8451	0.8481	0.8511	0.8541	0.8571	0.8601	0.8632	0.8662
41	sin	0.6561	0.6574	0.6587	0.6600	0.6613	0.6626	0.6639	0.6652	0.6665	0.6678
	cos	0.7547	0.7536	0.7524	0.7513	0.7501	0.7490	0.7478	0.7466	0.7455	0.7443
	tan	0.8693	0.8724	0.8754	0.8785	0.8816	0.8847	0.8878	0.8910	0.8941	0.8972
42	sin	0.6691	0.6704	0.6717	0.6730	0.6743	0.6756	0.6769	0.6782	0.6794	0.6807
	cos	0.7431	0.7420	0.7408	0.7396	0.7385	0.7373	0.7361	0.7349	0.7337	0.7325
	tan	0.9004	0.9036	0.9067	0.9099	0.9131	0.9163	0.9195	0.9228	0.9260	0.9293
43	sin	0.6820	0.6833	0.6845	0.6858	0.6871	0.6884	0.6896	0.6909	0.6921	0.6934
	cos	0.7314	0.7302	0.7290	0.7278	0.7266	0.7254	0.7242	0.7230	0.7218	0.7206
	tan	0.9325	0.9358	0.9391	0.9424	0.9457	0.9490	0.9523	0.9556	0.9590	0.9623
44	sin	0.6947	0.6959	0.6972	0.6984	0.6997	0.7009	0.7022	0.7034	0.7046	0.7059
	cos	0.7193	0.7181	0.7169	0.7157	0.7145	0.7133	0.7120	0.7108	0.7096	0.7083
	tan	0.9657	0.9691	0.9725	0.9759	0.9793	0.9827	0.9861	0.9896	0.9930	0.9965
Degs.	**Function**	**0′**	**6′**	**12′**	**18′**	**24′**	**30′**	**36′**	**42′**	**48′**	**54′**

45°–59.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
45	sin	0.7071	0.7083	0.7096	0.7108	0.7120	0.7133	0.7145	0.7157	0.7169	0.7181
	cos	0.7071	0.7059	0.7046	0.7034	0.7022	0.7009	0.6997	0.6984	0.6972	0.6959
	tan	1.0000	1.0035	1.0070	1.0105	1.0141	1.0176	1.0212	1.0247	1.0283	1.0319
46	sin	0.7193	0.7206	0.7218	0.7230	0.7242	0.7254	0.7266	0.7278	0.7290	0.7302
	cos	0.6947	0.6934	0.6921	0.6909	0.6896	0.6884	0.6871	0.6858	0.6845	0.6833
	tan	1.0355	1.0392	1.0428	1.0464	1.0501	1.0538	1.0575	1.0612	1.0649	1.0686
47	sin	0.7314	0.7325	0.7337	0.7349	0.7361	0.7373	0.7385	0.7396	0.7408	0.7420
	cos	0.6820	0.6807	0.6794	0.6782	0.6769	0.6756	0.6743	0.6730	0.6717	0.6704
	tan	1.0724	1.0761	1.0799	1.0837	1.0875	1.0913	1.0951	1.0990	1.1028	1.1067
48	sin	0.7431	0.7443	0.7455	0.7466	0.7478	0.7490	0.7501	0.7513	0.7524	0.7536
	cos	0.6691	0.6678	0.6665	0.6652	0.6639	0.6626	0.6613	0.6600	0.6587	0.6574
	tan	1.1106	1.1145	1.1184	1.1224	1.1263	1.1303	1.1343	1.1383	1.1423	1.1463
49	sin	0.7547	0.7559	0.7570	0.7581	0.7593	0.7604	0.7615	0.7627	0.7638	0.7649
	cos	0.6561	0.6547	0.6534	0.6521	0.6508	0.6494	0.6481	0.6468	0.6455	0.6441
	tan	1.1504	1.1544	1.1585	1.1626	1.1667	1.1708	1.1750	1.1792	1.1833	1.1875
50	sin	0.7660	0.7672	0.7683	0.7694	0.7705	0.7716	0.7727	0.7738	0.7749	0.7760
	cos	0.6428	0.6414	0.6401	0.6388	0.6374	0.6361	0.6347	0.6334	0.6320	0.6307
	tan	1.1918	1.1960	1.2002	1.2045	1.2088	1.2131	1.2174	1.2218	1.2261	1.2305
51	sin	0.7771	0.7782	0.7793	0.7804	0.7815	0.7826	0.7837	0.7848	0.7859	0.7869
	cos	0.6293	0.6280	0.6266	0.6252	0.6239	0.6225	0.6211	0.6198	0.6184	0.6170
	tan	1.2349	1.2393	1.2437	1.2482	1.2527	1.2572	1.2617	1.2662	1.2708	1.2753
52	sin	0.7880	0.7891	0.7902	0.7912	0.7923	0.7934	0.7944	0.7955	0.7965	0.7976
	cos	0.6157	0.6143	0.6129	0.6115	0.6101	0.6088	0.6074	0.6060	0.6046	0.6032
	tan	1.2799	1.2846	1.2892	1.2938	1.2985	1.3032	1.3079	1.3127	1.3175	1.3222
53	sin	0.7986	0.7997	0.8007	0.8018	0.8028	0.8039	0.8049	0.8059	0.8070	0.8080
	cos	0.6018	0.6004	0.5990	0.5976	0.5962	0.5948	0.5934	0.5920	0.5906	0.5892
	tan	1.3270	1.3319	1.3367	1.3416	1.3465	1.3514	1.3564	1.3613	1.3663	1.3713
54	sin	0.8090	0.8100	0.8111	0.8121	0.8131	0.8141	0.8151	0.8161	0.8171	0.8181
	cos	0.5878	0.5864	0.5850	0.5835	0.5821	0.5807	0.5793	0.5779	0.5764	0.5750
	tan	1.3764	1.3814	1.3865	1.3916	1.3968	1.4019	1.4071	1.4124	1.4176	1.4229
55	sin	0.8192	0.8202	0.8211	0.8221	0.8231	0.8241	0.8251	0.8261	0.8271	0.8281
	cos	0.5736	0.5721	0.5707	0.5693	0.5678	0.5664	0.5650	0.5635	0.5621	0.5606
	tan	1.4281	1.4335	1.4388	1.4442	1.4496	1.4550	1.4605	1.4659	1.4715	1.4770
56	sin	0.8290	0.8300	0.8310	0.8320	0.8329	0.8339	0.8348	0.8358	0.8368	0.8377
	cos	0.5592	0.5577	0.5563	0.5548	0.5534	0.5519	0.5505	0.5490	0.5476	0.5461
	tan	1.4826	1.4882	1.4938	1.4994	1.5051	1.5108	1.5166	1.5224	1.5282	1.5340
57	sin	0.8387	0.8396	0.8406	0.8415	0.8425	0.8434	0.8443	0.8453	0.8462	0.8471
	cos	0.5446	0.5432	0.5417	0.5402	0.5388	0.5373	0.5358	0.5344	0.5329	0.5314
	tan	1.5399	1.5458	1.5517	1.5577	1.5637	1.5697	1.5757	1.5818	1.5880	1.5941
58	sin	0.8480	0.8490	0.8499	0.8508	0.8517	0.8526	0.8536	0.8545	0.8554	0.8563
	cos	0.5299	0.5284	0.5270	0.5255	0.5240	0.5225	0.5210	0.5195	0.5180	0.5165
	tan	1.6003	1.6066	1.6128	1.6191	1.6255	1.6319	1.6383	1.6447	1.6512	1.6577
59	sin	0.8572	0.8581	0.8590	0.8599	0.8607	0.8616	0.8625	0.8634	0.8643	0.8652
	cos	0.5150	0.5135	0.5120	0.5105	0.5090	0.5075	0.5060	0.5045	0.5030	0.5015
	tan	1.6643	1.6709	1.6775	1.6842	1.6909	1.6977	1.7045	1.7113	1.7182	1.7251
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

60°–74.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
60	sin	0.8660	0.8669	0.8678	0.8686	0.8695	0.8704	0.8712	0.8721	0.8729	0.8738
	cos	0.5000	0.4985	0.4970	0.4955	0.4939	0.4924	0.4909	0.4894	0.4879	0.4863
	tan	1.7321	1.7391	1.7461	1.7532	1.7603	1.7675	1.7747	1.7820	1.7893	1.7966
61	sin	0.8746	0.8755	0.8763	0.8771	0.8780	0.8788	0.8796	0.8805	0.8813	0.8821
	cos	0.4848	0.4833	0.4818	0.4802	0.4787	0.4772	0.4756	0.4741	0.4726	0.4710
	tan	1.8040	1.8115	1.8190	1.8265	1.8341	1.8418	1.8495	1.8572	1.8650	1.8728
62	sin	0.8829	0.8838	0.8846	0.8854	0.8862	0.8870	0.8878	0.8886	0.8894	0.8902
	cos	0.4695	0.4679	0.4664	0.4648	0.4633	0.4617	0.4602	0.4586	0.4571	0.4555
	tan	1.8807	1.8887	1.8967	1.9047	1.9128	1.9210	1.9292	1.9375	1.9458	1.9542
63	sin	0.8910	0.8918	0.8926	0.8934	0.8942	0.8949	0.8957	0.8965	0.8973	0.8980
	cos	0.4540	0.4524	0.4509	0.4493	0.4478	0.4462	0.4446	0.4431	0.4415	0.4399
	tan	1.9626	1.9711	1.9797	1.9883	1.9970	2.0057	2.0145	2.0233	2.0323	2.0413
64	sin	0.8988	0.8996	0.9003	0.9011	0.9018	0.9026	0.9033	0.9041	0.9048	0.9056
	cos	0.4384	0.4368	0.4352	0.4337	0.4321	0.4305	0.4289	0.4274	0.4258	0.4242
	tan	2.0503	2.0594	2.0686	2.0778	2.0872	2.0965	2.1060	2.1155	2.1251	2.1348
65	sin	0.9063	0.9070	0.9078	0.9085	0.9092	0.9100	0.9107	0.9114	0.9121	0.9128
	cos	0.4226	0.4210	0.4195	0.4179	0.4163	0.4147	0.4131	0.4115	0.4099	0.4083
	tan	2.1445	2.1543	2.1642	2.1742	2.1842	2.1943	2.2045	2.2148	2.2251	2.2355
66	sin	0.9135	0.9143	0.9150	0.9157	0.9164	0.9171	0.9178	0.9184	0.9191	0.9198
	cos	0.4067	0.4051	0.4035	0.4019	0.4003	0.3987	0.3971	0.3955	0.3939	0.3923
	tan	2.2460	2.2566	2.2673	2.2781	2.2889	2.2998	2.3109	2.3220	2.3332	2.3445
67	sin	0.9205	0.9212	0.9219	0.9225	0.9232	0.9239	0.9245	0.9252	0.9259	0.9265
	cos	0.3907	0.3891	0.3875	0.3859	0.3843	0.3827	0.3811	0.3795	0.3778	0.3762
	tan	2.3559	2.3673	2.3789	2.3906	2.4023	2.4142	2.4262	2.4383	2.4504	2.4627
68	sin	0.9272	0.9278	0.9285	0.9291	0.9298	0.9304	0.9311	0.9317	0.9323	0.9330
	cos	0.3746	0.3730	0.3714	0.3697	0.3681	0.3665	0.3649	0.3633	0.3616	0.3600
	tan	2.4751	2.4876	2.5002	2.5129	2.5257	2.5386	2.5517	2.5649	2.5782	2.5916
69	sin	0.9336	0.9342	0.9348	0.9354	0.9361	0.9367	0.9373	0.9379	0.9385	0.9391
	cos	0.3584	0.3567	0.3551	0.3535	0.3518	0.3502	0.3486	0.3469	0.3453	0.3437
	tan	2.6051	2.6187	2.6325	2.6464	2.6605	2.6746	2.6889	2.7034	2.7179	2.7326
70	sin	0.9397	0.9403	0.9409	0.9415	0.9421	0.9426	0.9432	0.9438	0.9444	0.9449
	cos	0.3420	0.3404	0.3387	0.3371	0.3355	0.3338	0.3322	0.3305	0.3289	0.3272
	tan	2.7475	2.7625	2.7776	2.7929	2.8083	2.8239	2.8397	2.8556	2.8716	2.8878
71	sin	0.9455	0.9461	0.9466	0.9472	0.9478	0.9483	0.9489	0.9494	0.9500	0.9505
	cos	0.3256	0.3239	0.3223	0.3206	0.3190	0.3173	0.3156	0.3140	0.3123	0.3107
	tan	2.9042	2.9208	2.9375	2.9544	2.9714	2.9887	3.0061	3.0237	3.0415	3.0595
72	sin	0.9511	0.9516	0.9521	0.9527	0.9532	0.9537	0.9542	0.9548	0.9553	0.9558
	cos	0.3090	0.3074	0.3057	0.3040	0.3024	0.3007	0.2990	0.2974	0.2957	0.2940
	tan	3.0777	3.0961	3.1146	3.1334	3.1524	3.1716	3.1910	3.2106	3.2305	3.2506
73	sin	0.9563	0.9568	0.9573	0.9578	0.9583	0.9588	0.9593	0.9598	0.9603	0.9608
	cos	0.2924	0.2907	0.2890	0.2874	0.2857	0.2840	0.2823	0.2807	0.2790	0.2773
	tan	3.2709	3.2914	3.3122	3.3332	3.3544	3.3759	3.3977	3.4197	3.4420	3.4646
74	sin	0.9613	0.9617	0.9622	0.9627	0.9632	0.9636	0.9641	0.9646	0.9650	0.9655
	cos	0.2756	0.2740	0.2723	0.2706	0.2689	0.2672	0.2656	0.2639	0.2622	0.2605
	tan	3.4874	3.5105	3.5339	3.5576	3.5816	3.6059	3.6305	3.6554	3.6806	3.7062
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

75°–89.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
75	sin	0.9659	0.9664	0.9668	0.9673	0.9677	0.9681	0.9686	0.9690	0.9694	0.9699
	cos	0.2588	0.2571	0.2554	0.2538	0.2521	0.2504	0.2487	0.2470	0.2453	0.2436
	tan	3.7321	3.7583	3.7848	3.8118	3.8391	3.8667	3.8947	3.9232	3.9520	3.9812
76	sin	0.9703	0.9707	0.9711	0.9715	0.9720	0.9724	0.9728	0.9732	0.9736	0.9740
	cos	0.2419	0.2402	0.2385	0.2368	0.2351	0.2334	0.2317	0.2300	0.2284	0.2267
	tan	4.0108	4.0408	4.0713	4.1022	4.1335	4.1653	4.1976	4.2303	4.2635	4.2972
77	sin	0.9744	0.9748	0.9751	0.9755	0.9759	0.9763	0.9767	0.9770	0.9774	0.9778
	cos	0.2250	0.2232	0.2215	0.2198	0.2181	0.2164	0.2147	0.2130	0.2113	0.2096
	tan	4.3315	4.3662	4.4015	4.4374	4.4737	4.5107	4.5483	4.5864	4.6252	4.6646
78	sin	0.9781	0.9785	0.9789	0.9792	0.9796	0.9799	0.9803	0.9806	0.9810	0.9813
	cos	0.2079	0.2062	0.2045	0.2028	0.2011	0.1994	0.1977	0.1959	0.1942	0.1925
	tan	4.7046	4.7453	4.7867	4.8288	4.8716	4.9152	4.9594	5.0045	5.0504	5.0970
79	sin	0.9816	0.9820	0.9823	0.9826	0.9829	0.9833	0.9836	0.9839	0.9842	0.9845
	cos	0.1908	0.1891	0.1874	0.1857	0.1840	0.1822	0.1805	0.1788	0.1771	0.1754
	tan	5.1446	5.1929	5.2422	5.2924	5.3435	5.3955	5.4486	5.5026	5.5578	5.6140
80	sin	0.9848	0.9851	0.9854	0.9857	0.9860	0.9863	0.9866	0.9869	0.9871	0.9874
	cos	0.1736	0.1719	0.1702	0.1685	0.1668	0.1650	0.1633	0.1616	0.1599	0.1582
	tan	5.6713	5.7297	5.7894	5.8502	5.9124	5.9758	6.0405	6.1066	6.1742	6.2432
81	sin	0.9877	0.9880	0.9882	0.9885	0.9888	0.9890	0.9893	0.9895	0.9898	0.9900
	cos	0.1564	0.1547	0.1530	0.1513	0.1495	0.1478	0.1461	0.1444	0.1426	0.1409
	tan	6.3138	6.3859	6.4596	6.5350	6.6122	6.6912	6.7720	6.8548	6.9395	7.0264
82	sin	0.9903	0.9905	0.9907	0.9910	0.9912	0.9914	0.9917	0.9919	0.9921	0.9923
	cos	0.1392	0.1374	0.1357	0.1340	0.1323	0.1305	0.1288	0.1271	0.1253	0.1236
	tan	7.1154	7.2066	7.3002	7.3962	7.4947	7.5958	7.6996	7.8062	7.9158	8.0285
83	sin	0.9925	0.9928	0.9930	0.9932	0.9934	0.9936	0.9938	0.9940	0.9942	0.9943
	cos	0.1219	0.1201	0.1184	0.1167	0.1149	0.1132	0.1115	0.1097	0.1080	0.1063
	tan	8.1443	8.2636	8.3863	8.5126	8.6427	8.7769	8.9152	9.0579	9.2052	9.3572
84	sin	0.9945	0.9947	0.9949	0.9951	0.9952	0.9954	0.9956	0.9957	0.9959	0.9960
	cos	0.1045	0.1028	0.1011	0.0993	0.0976	0.0958	0.0941	0.0924	0.0906	0.0889
	tan	9.5144	9.6768	9.8448	10.02	10.20	10.39	10.58	10.78	10.99	11.20
85	sin	0.9962	0.9963	0.9965	0.9966	0.9968	0.9969	0.9971	0.9972	0.9973	0.9974
	cos	0.0872	0.0854	0.0837	0.0819	0.0802	0.0785	0.0767	0.0750	0.0732	0.0715
	tan	11.43	11.66	11.91	12.16	12.43	12.71	13.00	13.30	13.62	13.95
86	sin	0.9976	0.9977	0.9978	0.9979	0.9980	0.9981	0.9982	0.9983	0.9984	0.9985
	cos	0.0698	0.0680	0.0663	0.0645	0.0628	0.0610	0.0593	0.0576	0.0558	0.0541
	tan	14.30	14.67	15.06	15.46	15.89	16.35	16.83	17.34	17.89	18.46
87	sin	0.9986	0.9987	0.9988	0.9989	0.9990	0.9990	0.9991	0.9992	0.9993	0.9993
	cos	0.0523	0.0506	0.0488	0.0471	0.0454	0.0436	0.0419	0.0401	0.0384	0.0366
	tan	19.08	19.74	20.45	21.20	22.02	22.90	23.86	24.90	26.03	27.27
88	sin	0.9994	0.9995	0.9995	0.9996	0.9996	0.9997	0.9997	0.9997	0.9998	0.9998
	cos	0.0349	0.0332	0.0314	0.0297	0.0279	0.0262	0.0244	0.0227	0.0209	0.0192
	tan	28.64	30.14	31.82	33.69	35.80	38.19	40.92	44.07	47.74	52.08
89	sin	0.9998	0.9999	0.9999	0.9999	0.9999	1.000	1.000	1.000	1.000	1.000
	cos	0.0175	0.0157	0.0140	0.0122	0.0105	0.0087	0.0070	0.0052	0.0035	0.0017
	tan	57.29	63.66	71.62	81.85	95.49	114.6	143.2	191.0	286.5	573.0
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

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